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Thesis

UNIVERSITY OF ALBERTA

"FATIGUE CHARACTERISTICS OF A CEMENT STABILIZED SAND UNDER REPEATED STRESS REVERSAL"

by

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A THESIS

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "FATIGUE CHARACTERISTICS OF A CEMENT STABILIZED SAND UNDER REPEATED STRESS REVERSAL", submitted by Sadaqat Hasan Mir, in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

Soil cement has been selected by many highway engineers to produce low cost durable base material which would make use of locally available soils.

Considerable work has been done in the last decade on research and development of this material, and there has been much improvement in technique and control, making it possible to work on adequate scientific basis.

The American Society for Testing and Materials has thus set forth design criteria for use of soil cement in pavements.

Physical properties of soil cement, namely compressive strength, shear strength, density, flexure, compressive strength vs. flexural strength, modulus of rupture vs. modulus of elasticity have been studied in detail.

However, the importance of repeated loading on highway pavements, has been well recognised, in respect of a rational method for pavement design.

Studies so far made on cement-soil mixes under repeated loads have been in unconfined compression and triaxial states. This covers the complex problem of loading of road structures only partly.

This investigation describes the work carried out, in respect of repeated loadings in state of flexure, under complete stress reversal, as a preliminary step to evolve a method of design based on fatigue characteristics of cement stabilized soils.

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CHAPTER I

INTRODUCTION

1.1 General

Portland Cement stabilized soil has been extensively used as a base material for the low cost bituminous surfaced pavements for roads, streets, and air fields, and its use has steadily increased during the last decade.

One of the possible reasons for this is, the availability of data on physical properties of the material, procured after considerable research and development in many parts of the world. The Portland Cement Association of the U.S.A. have contributed much in this respect, and a report issued by Felt (1961) describes extensively the data relating to soil type, density, moisture content, modulus of elasticity, modulus of rupture, shear strength and volume change characteristics.

It has been shown that the above variables undoubtedly affect the strength characteristics of the soil cement in well related form.

The American Society for Testing and Materials has accordingly prescribed standards in respect of strength and durability for various types of soils, stabilized with portland cement, as entailed in the tests D559 and D560, for resistance to wetting and drying, and freezing and thawing.

In practice, it is apparent that the soil cement mixes may be designed to attain compressive strengths from a few hundred psi to more than 3,000 psi. But this is not enough. The more important properties of soil cement for the pavement, in addition to compressive strength and durability are the Modulus of Elasticity and Modulus of Rupture - the latter carrying more significance

in respect to methods of structural design of pavement, which at present are entirely empirical or semi-empirical in nature.

The three main types of failures in a road structure may be described as below:

(i) Consolidation failure

(ii) Shear failure

(iii) Flexure failure

The first two types are well recognized and the design methods employ static and gradually applied load parameters. As regards the flexure failure it has been established that as a pavement is subjected to load, the flexing of the structure beyond a certain limit of stress causes flexural failure. But if the pavement is subjected to repeated dynamic load, lesser than the static load, fatigue failure results, after a number of repetitions, depending upon the level of load applied. Considerable work has been done in the past on metals which has led to radical changes in the methods of design for machines and aircraft frames. Similarly, cement concrete like other materials is affected more by repeated loads than single load of same magnitude, and it has been found that flexural stresses higher than the critical level, cause fatigue failure in tension, while the compressive stress remains well below the point at which fatigue in compression would result. From this is follows that the fatigue under repetitions of flexural stress is the governing factor.

Soil cement being close to the cement-concrete requires similar study to determine its behaviour under repeated loadings in flexure.

1.2 Purpose of the Investigation and its Limitation

The present laboratory equipment is not so developed as to predict

the extent of flexure. The Benkleman Beam test however makes it possible to measure the flexure deformation under load on a constructed road. The curvature can also be measured. Plate bearing tests can also be used for assessing the deformation of constructed layers under loads, which enables to estimate the deflection and curvature. The American Society for Testing Materials however, has prescribed a method for measuring deformation employing a few cycles only, in their Test Method No. D1195-57, which is an approximate approach to practical problem.

The studies so far made on soil cement employing repeated loading are only in unconfined compression and triaxial compression states and cover the problem only partly. The effect of repeated load on soil cement in flexure does not appear to have been studied at any stage, as evident from not only the commonly referred sources of literature from Europe and America, but also from the publications issued in Africa and Australia.

The object of this investigation, therefore, is to study the behaviour of soil cement under repeated loads in a state of flexure as a preliminary step to develop eventually a rational method to design pavements with stabilized bases. This investigation forms part of continuing research on stabilization of highway materials under the Alberta Co-operative Highway Research Programme, comprising the Provincial Department of Highways, the Alberta Research Council, and Department of Civil Engineering, University of Alberta, Edmonton.

Though this subject has extensive scope, involving many variables, the study was limited to the following only.

(i) Cement content

(ii) Age

(iii) Stress level

(iv) Frequency of cycles

A cantilever type constant stress amplitude fatigue machine was developed after Pell (1960) and used throughout the investigation.

The results have been presented in the form of conventional stress versus no. of cycles diagrams for three cement contents, and two ages.

1.3 Organization of the Thesis

The thesis proper begins from Chapter II with a review of literature and general concepts involved in fatigue characteristics of many materials. This chapter covers the abbreviated history of work conducted on fatigue, describing the studies made in the past in general and discussions on more recent work on cement stabilized soils in particular.

Chapter III describes the materials used for the investigation.

Chapter IV deals with the testing programme and covers the preliminary investigations, the testing device, and procedure.

Chapter V contains presentation and discussion of test results.

Chapter VI comprises of conclusions and recommendations.

The Appendices follow the Bibliography, and contain detailed test data.

CHAPTER II

REVIEW OF LITERATURE

2.1 General

Since 1959 the Department of Highways of the Province of Alberta has carried out an extensive construction programme utilizing cement-stabilized bases, for primary and secondary highways.

A total of 385 miles of soil cement highways were constructed up to the end of 1964, according to figures obtained from the Highways Division of the Alberta Research Council. This represents about ten percent of the total paved highways mileage in the Province of Alberta.

Though various aspects of static load application have been studied in detail, the fatigue characteristics of cement-soil are still in preliminary stage.

An approach to this aspect can be made on the basis of fatigue studies for various other materials made in the last few decades. These investigations resulted in revolutionizing the design criteria for almost all the materials so far studied, and it will be appropriate to have a brief review of some of the investigations made so far.

However before entering into the review, it will be necessary to explain the term "Endurance Limit" or "Critical Stress" - commonly implied in the fatigue investigations. According to Timoshenko (1956), the stress at which the stress - number of cycles curve approaches, asympotically, the horizontal line, is called the Endurance Limit or Critical Stress.

When any material is stressed at that level, it can take infinite number of cycles without failure.

However it is not always that such limit exists, as in the case of non-ferrous metals.

2.2 Metals

Investigation of fatigue of metals was started as far back as in 1829 when Albert subjected mine hoist chains to repeated loading. He was followed by many scientists and engineers.

The failure of steel due to fatigue was well understood long ago. Similar is the case with non-ferrous metals, and it has been established that a material will fail more quickly under repeated loads of lesser magnitude, than the static or slowly applied load.

According to Timoshenko (1949), the relation between the repeated load to failure and the stress applied on ferrous and non-ferrous metals is given in FIGURE 1.

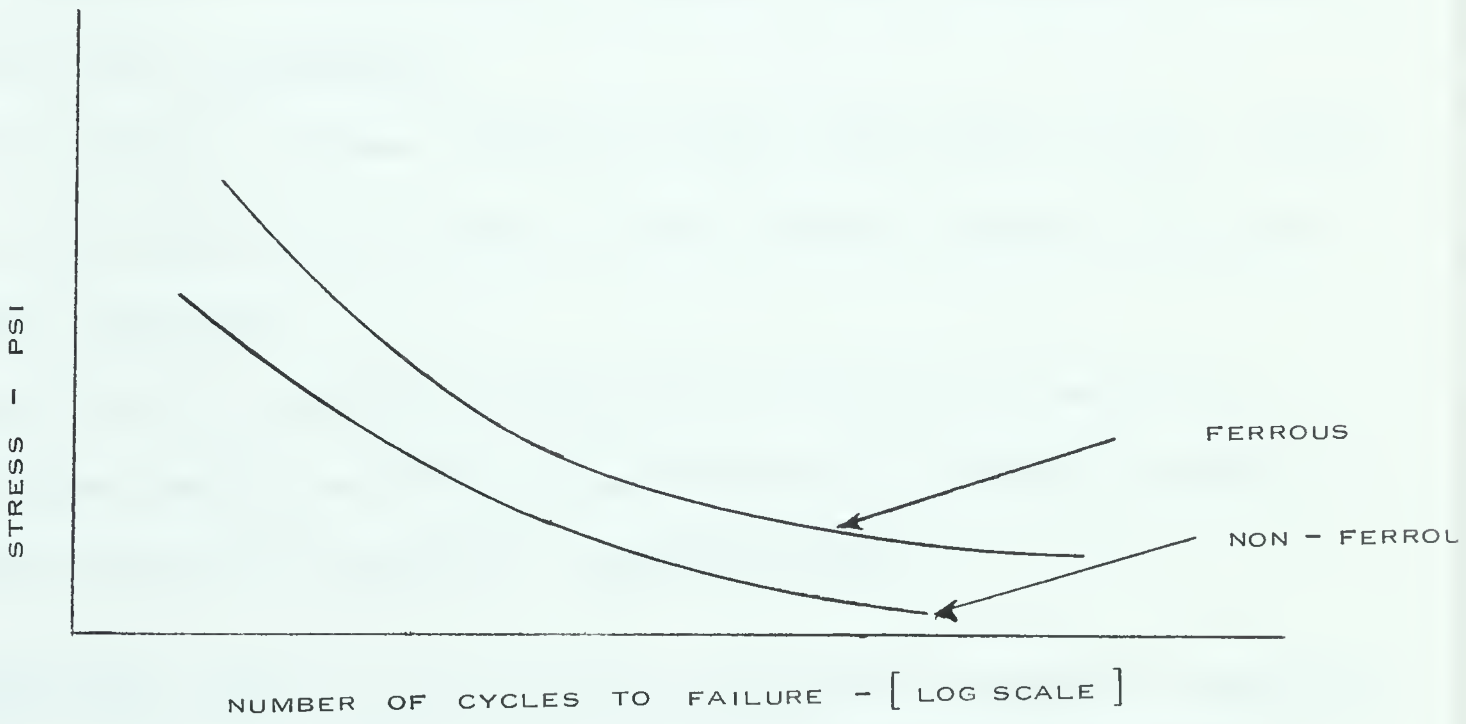


FIGURE I. TYPICAL S-N CURVES FOR FERROUS AND NON-FERROUS METALS .
[AFTER TIMOSHENKO]

Timoshenko has stated that:

> "Large amount of experimental data accumulated has not yet made it possible to establish such a correlation. As a rough estimate the endurance limit for ferrous metals under repeated stresses can be taken equal to 0.40 to 0.55 times the ultimate strength obtained in the usual way from a tensile test."

Such endurance limit does not exist in case of non-ferrous metals, and according to Timoshenko, it ranges from 0.21 to 0.49 times the ultimate strength as obtained in the ordinary static tension test.

2.3 Concrete

The study of fatigue in non-metallic materials like concrete was however begun only in the second half of the nineteenth century.

A comprehensive review of investigations and research work has been presented by Nordby (1958) which throws ample light on the history of fatigue research on concrete. He has mentioned the work carried out by Feret in France in 1906 as well as the investigations conducted by Department of Highways, Illinois, (1921 - 1923) and also at the Purdue University (1923 - 1924) on flexural fatigue, as the importance of repeated loads on highway pavements became more and more acknowledged.

It was found by Clemmer (1924) and Older (1924) that a higher stress level caused early fatigue failure and in case of earlier stress history the endurance limit was raised.

Describing the complicated phenomenon of fatigue of concrete as still inconclusive, Nordby has mentioned many features of fatigue studies in his review more pertinent of which are reproduced below:-

"(i) The fatigue limit of plain concrete subjected to repeated compressive stresses ranging between zero to maximum is 50-55 percent of the ultimate static compression strength.

(ii) The fatigue limit of plain concrete subjected to repeated flexural loads is about 55% of the static ultimate flexure stress, although there was a variance of 33 to 64 percent depending upon other variables such as age, moisture content, curing and aggregates.

(iii) The fatigue limit for concrete in tension is about 55% of the modulus of rupture.

(iv) Age and curing have a decisive effect on the fatigue strength. Inadequately aged and cured specimen is less resistant to fatigue than well aged and cured concrete.

(v) The effect of saturation is unknown, however one investigator reports a fatigue limit as low as 33% of the ultimate static strength.

(vi) Rate of testing between 70 and 440 cycles per minute has little effect on fatigue strength. Slow rates (about 10 cycles per minute) seem to decrease the fatigue strength. The creep phenomenon is so inter-related with long-time fatigue loading that it is difficult to separate the effects of the two.

(vii) Rest periods seem to increase the endurance of concrete although tests results are scanty.

(viii) Fatigue strength decreases slightly with leaner mixes and higher water cement ratios (data non-conclusive)."

2.4 Bituminous Materials

Larew (1960) has reviewed the work done on fatigue failures of bituminous mixes which can be stated briefly as below:-

"Only minor interest has been shown in the behaviour of bituminous materials under the action of repeated loads prior to the early 1950's. However, the observance of what appeared to be fatigue failures of flexible pavements, has created considerable interest in this phenomenon during the last ten years.

Monismith (1958) has reported the results of preliminary laboratory studies of the factors affecting the asphaltic pavement flexibility, in his review of the research carried out by many investigators. All these tests generally employed beams in flexure, and the results indicate that asphaltic materials exhibit an S-N diagram which in some respects was similar to concrete. Whether asphalt has a true endurance limit, has not yet been established. An effect of work hardening was noted when lighter loads were first cycled on the specimen and later increasingly larger loads were applied. Density, aggregate size, gradation and type, asphaltic properties and content, temperature, and the effects of weathering were but a few of the factors which early investigators have recognized as affecting the fatigue properties of asphaltic materials."

Monismith gave a preliminary report of a proposed comprehensive investigation of the fatigue properties of asphalt, employing carefully prepared and compacted beam specimens. These beams were placed upon a circular base which was supported by many individual coil springs and then centrally loaded with either a static or repeated load.

Frequency, duration of load cycle, and temperature of test were carefully controlled. The effects of asphalt content, magnitude of applied load and temperature upon the fatigue properties, of both dense graded and an open graded mixture were studied. Monismith reported as follows:-

"For the particular mixtures, rate and number of load applications, and temperatures studied, the fatigue behaviour of the asphaltic paving mixtures are dependent upon the amount of asphalt, the magnitude of the applied load and the gradation of the aggregate.

(a) For the dense-graded mixture under a given magnitude of load, the fatigue effect decreases with increasing asphalt content.

(b) For the dense-graded mixtures the fatigue effect becomes more pronounced with increasing magnitude of load.

(c) In the open-graded mixtures, the fatigue effect is more pronounced for the dense-graded mixtures at a given magnitude of load. Although there are too few tests to determine any general conclusions relative to the behaviour of open-graded mixtures, their behaviour in the laboratory tests under repeated load would indicate that critical examination of this characteristic is required both in the laboratory and in the actual pavement."

Wood and Goetz (1956 and 1957) and Goetz, McLaughlin and Wood (1957) have reported the results of repeated load tests of bituminous mixtures in which cylindrical specimens were tested in triaxial and unconfined compression. In this respect their tests differed from those described previously. They studied the effects of such variables as temperature, confining pressure, magnitude of repeated axial stress, and rate of deformation. The repeated axial stresses were not reversed, but were compressive in every case. They generally applied fewer than twenty repetitions of axial stress to a given specimen. For the materials and mixtures studied, and for a given set of test conditions, they found that for levels of repeated axial stress, equal to one-

fourth the static compressive strength, the relationship between permanent sample deformation and number of repetitions, plotted on a logarithm scale was linear. For higher levels of repeated stress equal to one-half the static compressive strength, their relationship was, for the first few cycles, linear but became non-linear with the deformation increasing rapidly upon the application of only a few additional cycles of repeated stress. The highest level of repeated stress for which the above mentioned relationship was linear was called the endurance limit. The ratio of this endurance limit to the compressive strength appeared to be little affected by the confining pressure and to vary between one-fourth and one-half in all cases studied."

Monismith (1961), in his subsequent work has further summarized the research related to the behaviour of asphalt mixtures in repeated flexure, and has reported as follows:-

> "A number of mix variables would appear to have an effect on fatigue behaviour of asphalt concrete. Chief among these is the asphalt content of the mixture; that is the higher the asphalt content, the longer the fatigue life.
>
> For mixes which have been properly designed, it would appear that the magnitude of the tensile strain repeatedly applied would be an excellent criterion for failure, this in preference to a limiting value of deflection. Moreover, it may be possible to obtain at least an approximate estimate of the fatigue life of a pavement so long as the bending deformations associated with different classes of axle loads can be ascertained."

He has concluded that:-

"(i) For the range of frequencies and at the particular temperature studied, the frequency and the type of asphalt would appear to have little effect on asphalt mixture behaviour in repeated flexure.

(ii) From the tests in which a stress reversal was applied to beams in repeated flexure, and for temperature and frequency used in this investigation, it would appear that stress reversal has little effect on fatigue behaviour so long as the maximum bending strains are the same in both reversed bending and unidirectional bending."

Some more work has been carried out by Pell (1962) subsequent to Monismith. Pell has summarized his work in the following comments:

"(i) The fatigue life of the sand-sheet mix under alternate bending stress of constant amplitude is highly temperature dependent - the lower the temperature the longer is the life.

(ii) The fatigue limit is also dependent to some extent on the speed of loading - the lower the speed the shorter the life.

(iii) The relationship between the logarithm of the stress and the logarithm of the number of cycles to failure appears to be linear at all temperatures and speeds over wide range of stress, although there is some evidence of non-linearity at very high stresses.

(iv) The slope of the plot of log-stress against log-cycles considering the experimental scatter present, does not appear

to be dependent on the temperature or the speed."

2.5 Stabilized Soils

As stated in Paragraph 2.1, cement stabilized soil has been utilized extensively for the highway pavements in the last decade. Though considerable work has been done on its research and development, this has been, strictly speaking, limited to strength and durability, involving static loads. The factors affecting these characteristics have been very well explained by Davidson (1961).

Metcalf and Fryden (1962) have stressed the need of study of the cement stabilized soils in a state of tension. They have described the present design criteria as unsuitable for all climates, and also due to the fact that they bear no relation to stresses developed in the pavement and consequently it would be unreasonable to use them in a general manner.

Similarly experience in Great Britain has shown that pavements with soil cement provided according to the design criteria, have performed the worst, in case of certain fine single-sized sands. Therefore it becomes necessary to consider different aspects of loading on the highway pavements, other than the present design criteria (lee and Croney 1962).

Some study of effect of repeated loads on soil cement, however has been carried out only in the recent years as evident from the available records.

Larew, Whittle, Wiley and Wilson (1962) have investigated the effect of repeated loading in triaxial state on a micaceous soil stabilized with portland cement.

Their scope of study was however directed to know the effect of repeated loads upon the stress-deformation characteristics and resilient properties of elastic micaceous soils.

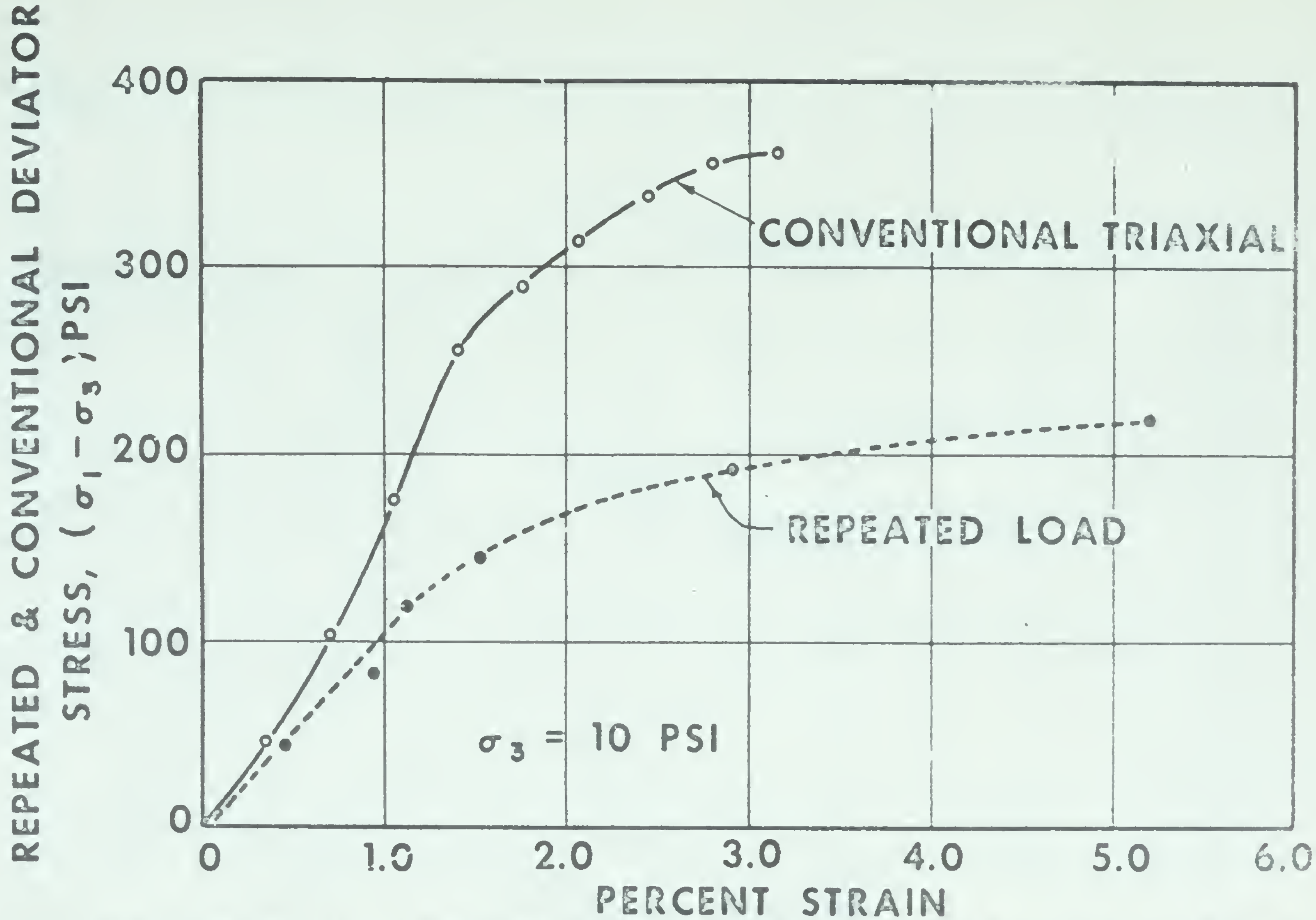


FIGURE 6. REPEATED LOAD AND CONVENTIONAL STRESS VS. STRAIN CURVES FOR GLENELG C + 5 % TYPE III CEMENT.

FIGURE 3. [AFTER LAREW, WHITTLE, WILEY, WILSON]

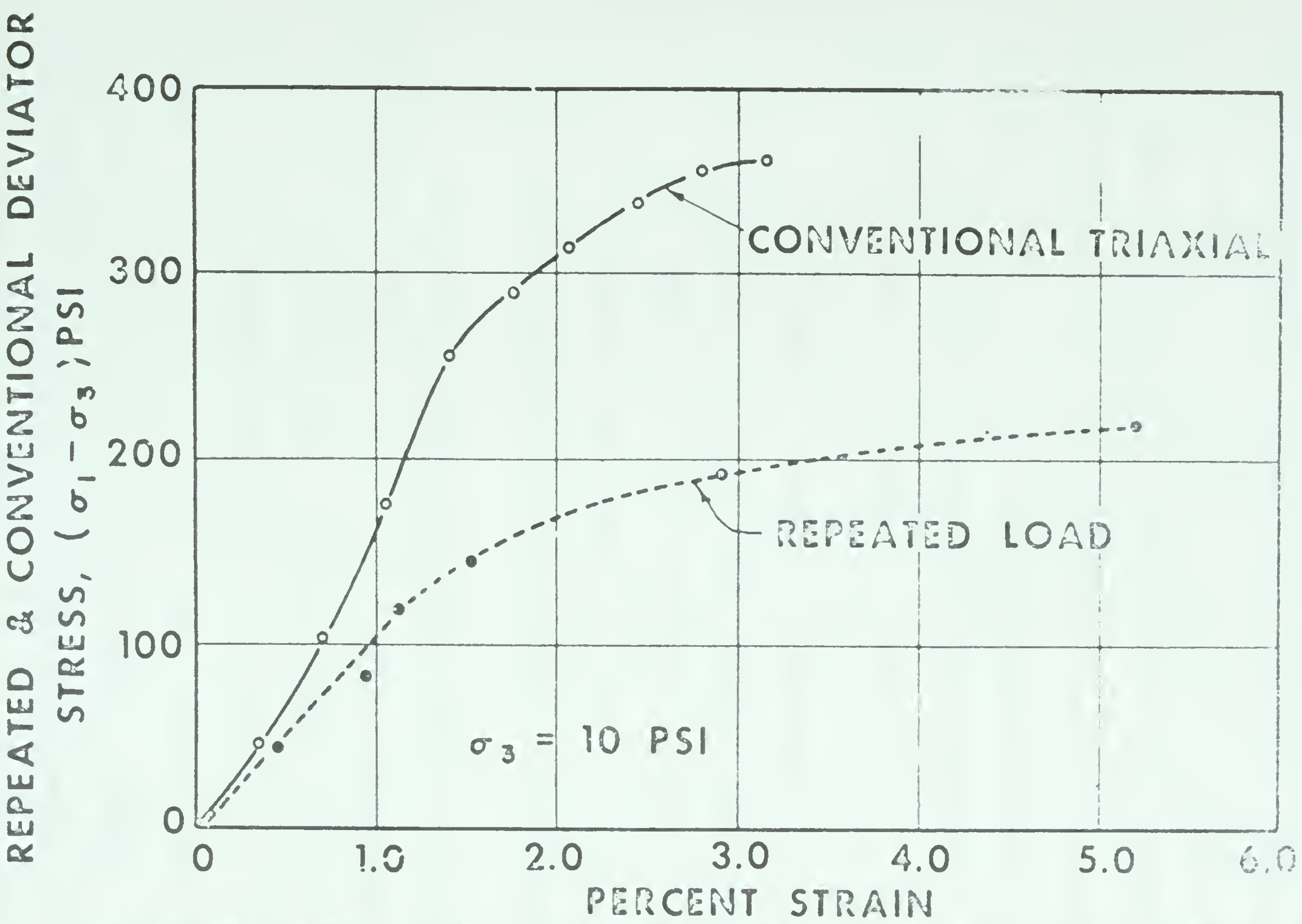


FIGURE 6. REPEATED LOAD AND CONVENTIONAL STRESS VS. STRAIN CURVES FOR GLENELG C + 5 % TYPE III CEMENT.

FIGURE 3. [AFTER LAREW, WHITTLE, WILEY, WILSON]

Their findings are illustrated by FIG. No. 2 and No. 3. FIG. 2 shows families of curves for repetitions of loading versus deformation for Clenelg soil + 5% Type III cement at different $\Delta\sigma_R/\Delta\sigma_S$ values.

FIG. 3 compares the stress strain curve for one particular soil, namely, Clenelg C, with five percent Type III cement, as obtained in the conventional triaxial test with that obtained by repeated load triaxial tests. It can be readily seen that the repeated load strength and stiffness for this cement modified soil is considerably less for repeated loads than for conventionally applied loads. However, the strain at failure is essentially the same in both the cases, according to Larew, Whitle and others.

Similar was the case with soils treated with ten percent cement. One of their relevant conclusions is described below.

> "The ultimate strengths of stabilized soils (and cement modified soils), as determined with repeated loads, was considerably less than the ultimate strength obtained for identical samples using conventional loading apparatus; however the strain at failure remained nearly the same for both types of loading."

Fossberg and Gregg (1963) have worked on wind blown sand stabilized with portland cement in South Africa. They applied repeated stresses in unconfined compression state. They also found that the critical strength value for this material was apparently 60 percent of the ultimate compressive strength in static loading. FIG. 4 shows typical results of repeated-load laboratory testing, with various percentages of cement. They have recommended, that, in addition to density and strength requirements, the measurement of flexural behaviour under repeated loading is also necessary.

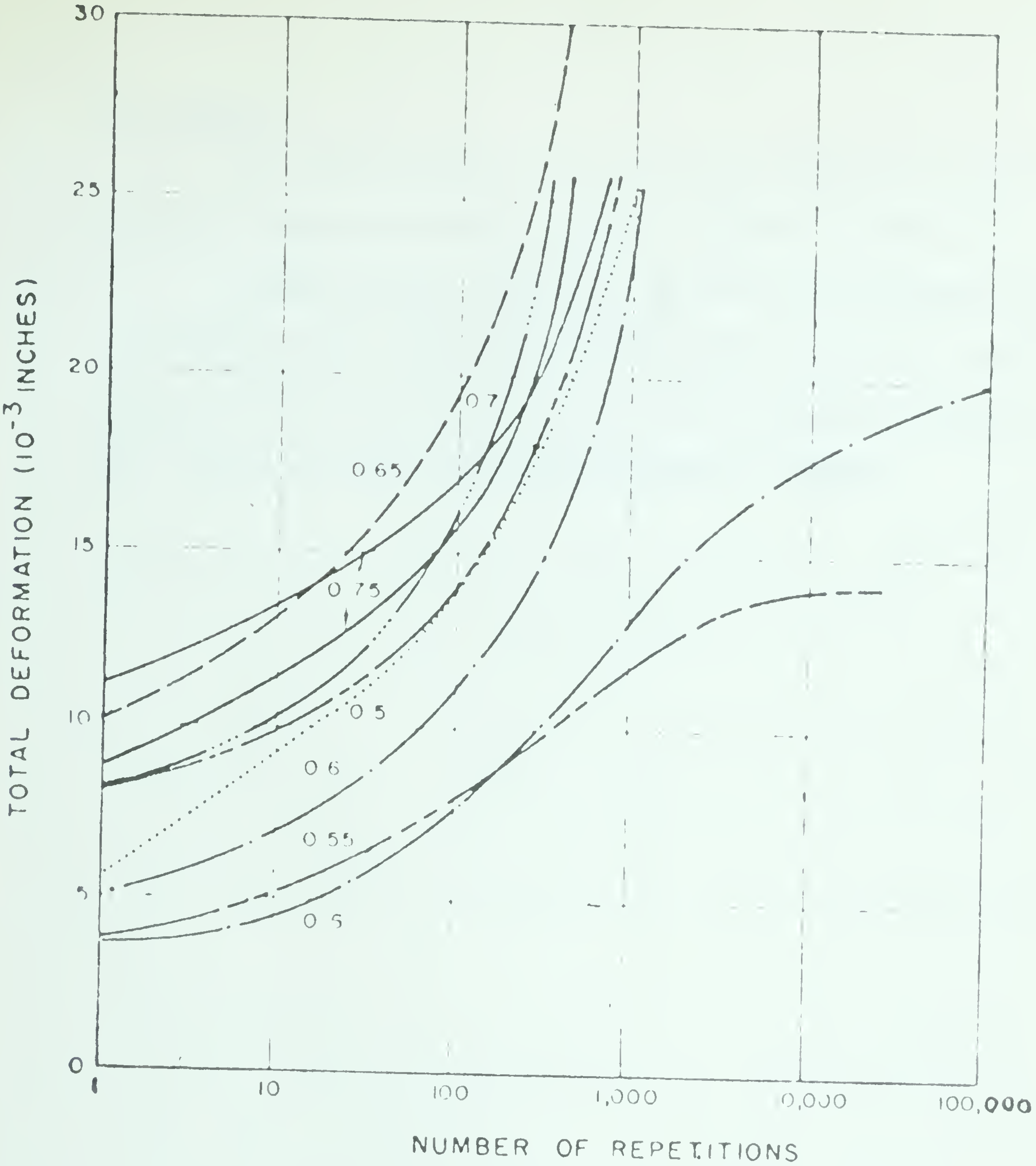


FIGURE 4. [AFTER FOSSBERG AND GREGG]

Fig. 6 -- Relationship between number of repetitions of load and deformation in unconfined compression testing of sand-cement specimens

LEGEND

Ratio $\frac{\sigma_r}{\sigma_f}$

0.75

0.70

0.65

0.60

0.55

0.50

Cement content = 6%

Dry density 118.9 lb/cu.ft.

Moisture content at preparation 10.8%

σ_r Repeated axial stress.

σ_f = Unconfined compressive strength at 7 days.

2.6 Summary

The review presented in the preceding paragraphs covers the behaviour of various materials under the action of repeated loading.

Though a direct comparison can not be made between the two studies of stabilized soils conducted by Larew, Wiley and others, and, Fossberg and Gregg, it may be seen that the results of both studies indicate lower strength under repeated stresses as compared to static loading.

CHAPTER III

MATERIALS

3.1 Sand

On the many projects undertaken by the Alberta Highways Department, sands from various sources were used. Granulometric properties of some of the sands proposed for 1964 projects are shown in TABLE 1.

Klein pit sand, used on Project 44-A-1, and located about 80 miles north of Edmonton was selected for the laboratory sork since it was representative of many other sand deposits. Routine tests for particle size distribution, dry density, optimum moisture and classification were run for this programme.

Granulometric properties and other information are given below:-

Location	N.E. 16-63-26-4
A.A.S.H.O. Classification	A-3
Specific Gravity	2.67
Uniformity Coefficient	2.82
Grading Modulus	15

GRANULOMETRIC PROPERTIES OF VARIOUS SANDS USED

FOR DIFFERENT PROJECTS

SERIAL No.	PROJECT	SAMPLE No.	PERCENT BY WT. RETAINED BETWEEN SIEVE SIZE 3/4"- #4	#4- #8	#8- #16	#16- #30	#30- #50	#50- #100	#100- #200	PASS #200	GRADING MODULUS
1	2-G-2	SAS-A223 Morawski	-	-	1	3	23	53	12.4	7.6	19
2	"	SAS-A222 Heart River	-	-	-	1	10	60	24.2	4.8	21
3	42-A	SAS-A233 E. Pierce	-	2	4	7	23	42	12.8	9.2	19
4	"	SAS-A232 Robertson	-	-	2	8	33	43	8.6	5.4	16
5	12-C	SAS-A220 Ripley	-	-	-	0.5	20.5	57	11.8	10.2	21
6		SAS-A217 White	-	-	-	1	11	53	25	20	30
7	44-A-1	SAS-A258 Klein	2	1	1	6	27	38	14.9	10.1	20
SURFACE AREA FACTORS (ALBERTA HIGHWAYS DEPARTMENT)			-	1	2	4	8	16	32	64	$GM = \frac{S.A.F.}{100}$

Dry Density	104 pcf
Optimum Moisture	13.5%

3.2 Cement

In the earlier stage of preliminary investigation, Type I, normal Portland Cement was utilized. Later on it was changed to Type III, High Early Strength Cement, to speed up the testing programme for three days and fourteen days strength.

The cement was placed in double plastic bag to avoid moisture adsorption and hydration. Fresh supply was used every month.

CHAPTER IV

TESTING PROGRAM AND APPARATUS

4.1 Outline of Testing Programme

The testing programme comprised of two stages, namely, the preliminary investigations and the fatigue tests proper.

Preliminary investigations involved:-

(i) Determination of design density.

(ii) Flexure and Compression tests.

(iii) Determination of compaction procedure for production of fatigue test specimens.

4.2 Design Density

The flexure beams as well as the fatigue test specimens were to be moulded at maximum dry density achieved at optimum moisture. It was decided to have three series of tests, using six, eight and ten percent of cement in each series. Standard Proctor tests were conducted for all the three mixes. The results have been tabulated below.

Cement by Weight	Optimum Moisture	Max. Dry Density - pcf
6%	10% by weight	117.3
8%	9.8% "	120.6
10%	9.6% "	122.1

4.3 Fatigue Test Specimens

A cylindrical specimen 2 inch in diameter and 8 inch long was used for the fatigue tests. The mold for this specimen is shown in Photograph 4. Fatigue tests were conducted at various levels of stress, based on modulus of rupture, which in turn depends upon the density of soil-cement mix. It was therefore necessary to ensure that specimens for fatigue test were moulded to the design density of flexure test specimens. This posed an intricate proposition because of possibility of density variation within the specimen.

Various procedures were tried to find out the one which could produce identical specimens, with uniform density gradient. The method finally adopted is described below and the curves for density gradient for a few samples are shown in FIG. No. 5.

Parts of the mould used for casting fatigue specimens were as below.

(i) Main tube 9-1/2" long with rebated top.

(ii) Extension tube 3" long bottom rebated.

(iii) Top plunger 1-15/16" diameter and 4-1/2" long.

(iv) Bottom plunger 1-15/16" diameter and 2" long.

(v) Specimen pallet 1/8" thick.

(vi) Base plate and spacer bars.

(vii) Extruder pistons.

(viii) Semi-split receptacle tube.

Compaction Method

Weighed quantity of the loose mix was taken and placed in four layers. The compaction was done by rectangular tamper, similar to the one used in

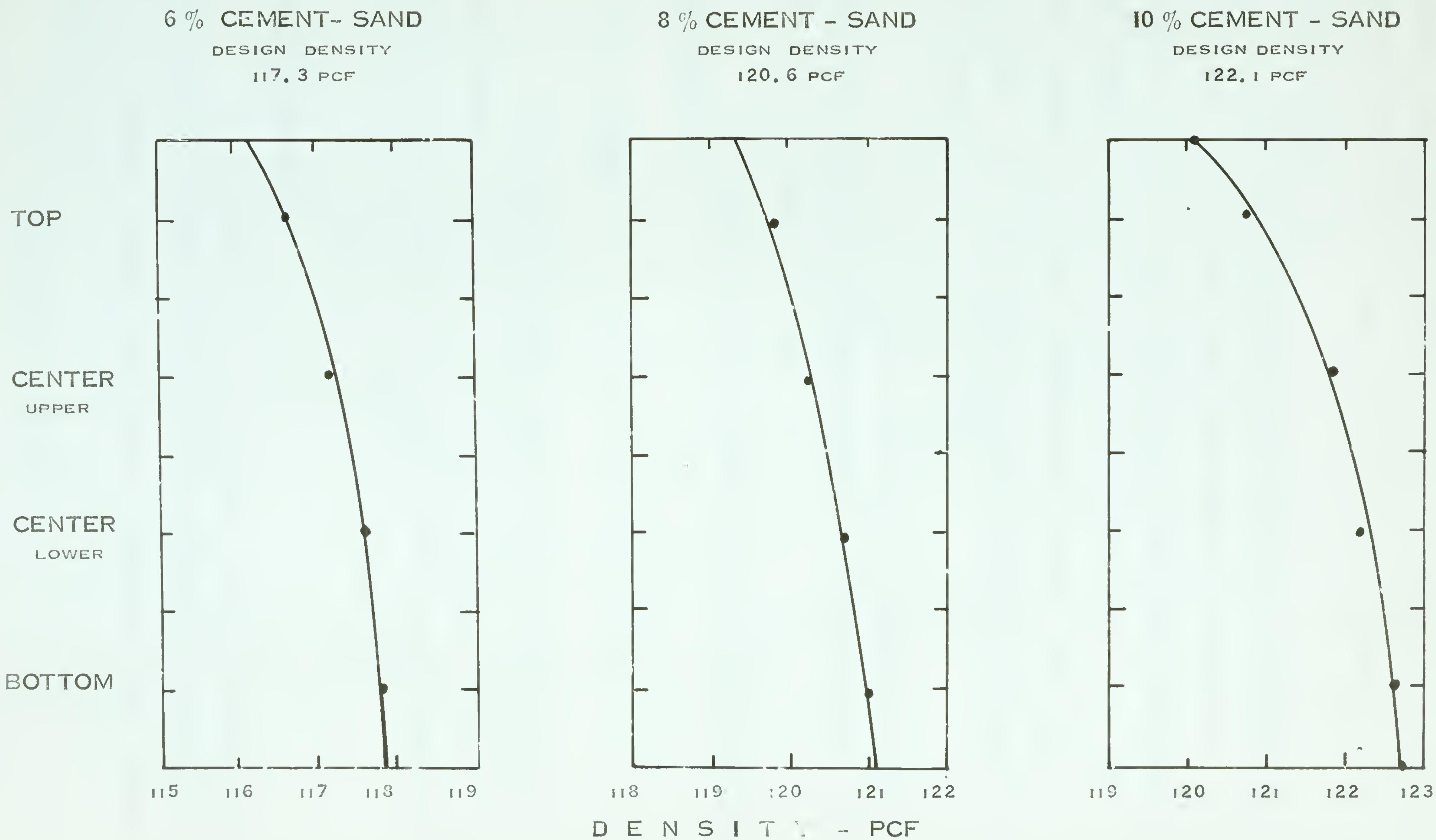


FIGURE 5. DENSITY GRADIENT FOR FATIGUE TEST SPECIMENS. EACH POINT REPERESENTS FOUR RESULTS.

Hubbard Field Density Apparatus, to avoid formation of compaction planes. Before adding the next layer, the material was loosened at the surface to have an adequate bond.

The first filling was given ten blows, the second and third twenty blows each and the fourth one fifteen blows. The mould with top and bottom plungers in position was then placed in Tinius Olson Compression machine and compression applied till the top plunger moved to its limit. Compression was released, top plunger withdrawn and specimen pallet placed on top in the mould. The bottom spacers were then removed and compression applied till the bottom plunger reached its limit.

To allow for rebound, compression was applied to get the plunger in by 1/16" more and by holding the load for twenty seconds - which was found sufficient to retain the size.

The specimen was then extruded by piston in the receptacle tube (Photograph 4).

Curing

The specimen was kept during the day covered with plastic sheet to avoid excessive moisture loss and in the evening were removed to the moisture room and covered by plastic sheet and allowed to cure in 100% R.H. for the various periods, when it was tested in moist condition.

4.4 Testing Device

The testing device is essentially a cantilever type constant bending stress machine in which stress of desired magnitude is applied to the specimen and when rotated it varies from maximum to minimum in each rotation in sinusiodal form.

This is illustrated in FIG. 6.

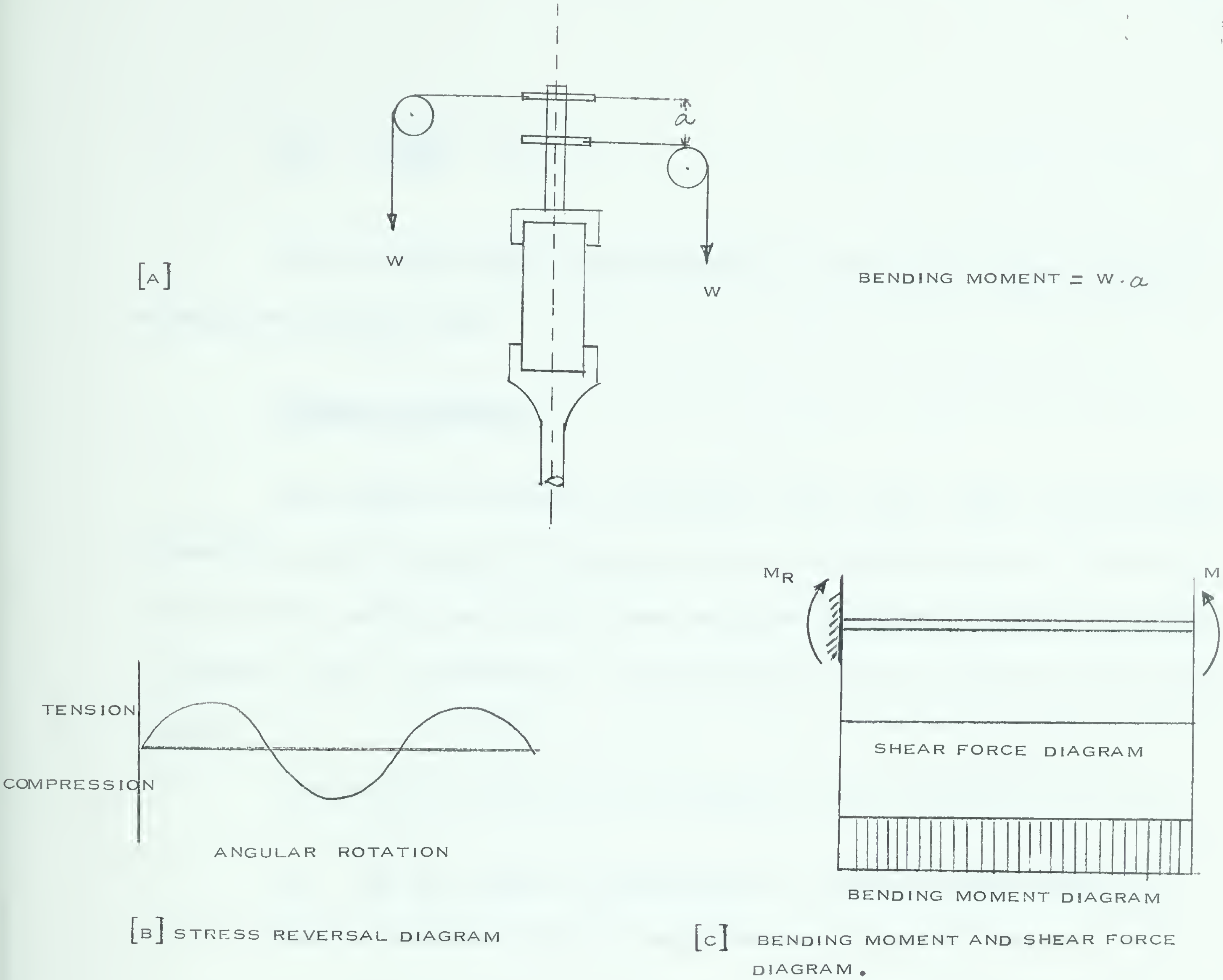


FIGURE 6. PRINCIPLE OF CANTILEVER TYPE CONSTANT STRESS AMPLITUDE FATIGUE MACHINE.

If W = two equal and opposite weights applied to the specimen in pounds

a = distance between the two weights in inches

M = bending moment = Wa inch lbs.

f = extreme fibre stress in psi

d = diameter of the specimen in inches

y = distance from neutral axis to extreme fibre = $d/2$ inches

I = moment of Inertia = $\dfrac{d^4}{64}$ in.^{4}

Then $\dfrac{f}{y} = M/I$

or $f = \frac{My}{I} = \frac{32Wa}{d^3}$ psi

This is the simple relationship for finding the weight required to produce any stress level.

Design of Machine

The design of machine is actually after Pell (1962) of Nottingham University, used by him for fatigue study of bituminous mixes. However, to suit for this particular study it was modified as shown in detail drawings in Plates I and II (Appendix D). Photographs 7(A) and 7(B) show completed machine.

The salient features of the machine can be described as below.

(1) The top frame is adjustable to a fairly large extent so that a specimen of any length between 4" and 12" can be used.

(2) The frequency can be varied between 100 and 1000 cycles per minute at four rates namely 100, 250, 500 and 1000 cycles per minute.

(3) The machine is simple in construction and easy to operate.

(4) The cycle counter being at top of specimen, it stops at failure, without involving complicated devices.

(5) It can be utilized for fatigue testing on any non-metallic material, for studies involving flexure under constant stress amplitude.

4.5 Mounting of Specimen

The mounting of specimen in the machine involved four steps:-

(i) Fixing end caps: - The end pieces were required to provide an adequate grip area to the specimen ends. The end pieces were fixed to the specimen by molten sulphur. Photo. 4 and 6, show the device for concentric fixing of end pieces, leaving a clear length of 4 inches.

(ii) Mounting in the chucks:- After sulphur casting the specimen was placed in the bottom chuck and screwed by the chuck nut.

(iii) Cutting groove: - Having fixed the specimen at the lower end, a V-groove was cut in the middle of the clear length to have a reduced diameter of 1.9" and width of 1/8". The provision of this groove was necessary to have stress concentration and thus to restrict the failure to this point; away from the ends.

(iv) Fixing the top chuck: - The specimen after having been grooved, top chuck was placed on top of the end piece and screwed in position.

4.6 Applying the Load

The next step involved the application of load as calculated for a particular stress level, in both the pans, simultaneously, by gradually pouring the equal quantity of lead shots. This is necessary to avoid the moment developed by single or unequal loads.

The machine was then started which ran till failure.

4.7 Summary of Procedure

For all the three series, tests were carried out for ages at 3 and 14 days. A summary of tests is shown on the next page. The specimens were stressed at different levels expressed as a percentage of the Modulus of Rupture, R , determined by flexure tests on beams according to ASTM Method No. D1635-63. The modulus of rupture, though a fictitious value, is considered as an index of flexural strength, for practical purposes. Since the relationship between stress, bending moment and moment of inertia is applicable the values of R obtained for rectangular beam sections could also be applied to cylindrical sections.

The provision of a notch to the specimen, caused stress concentration, with the result that the stresses actually induced were higher than calculated. The effect of this was however ignored.

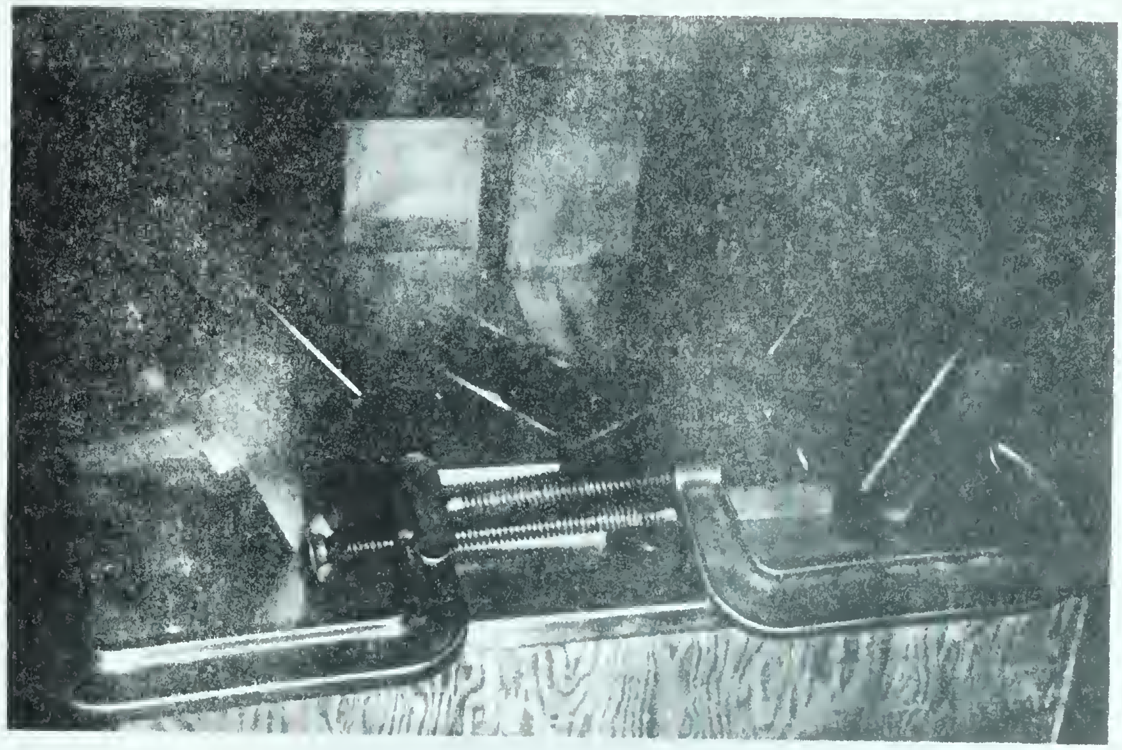
The specimens were subjected to stress reversal till they failed. Thus number of cycles to failure for each stress level were recorded.

The frequency for all the tests in the main programme was kept at 100 cycles per minute. The testing time involved, varied from a few seconds at higher stress levels to a few days at low stress levels. In the latter case the specimens were run up to one million cycles, a limit arbitrarily chosen.

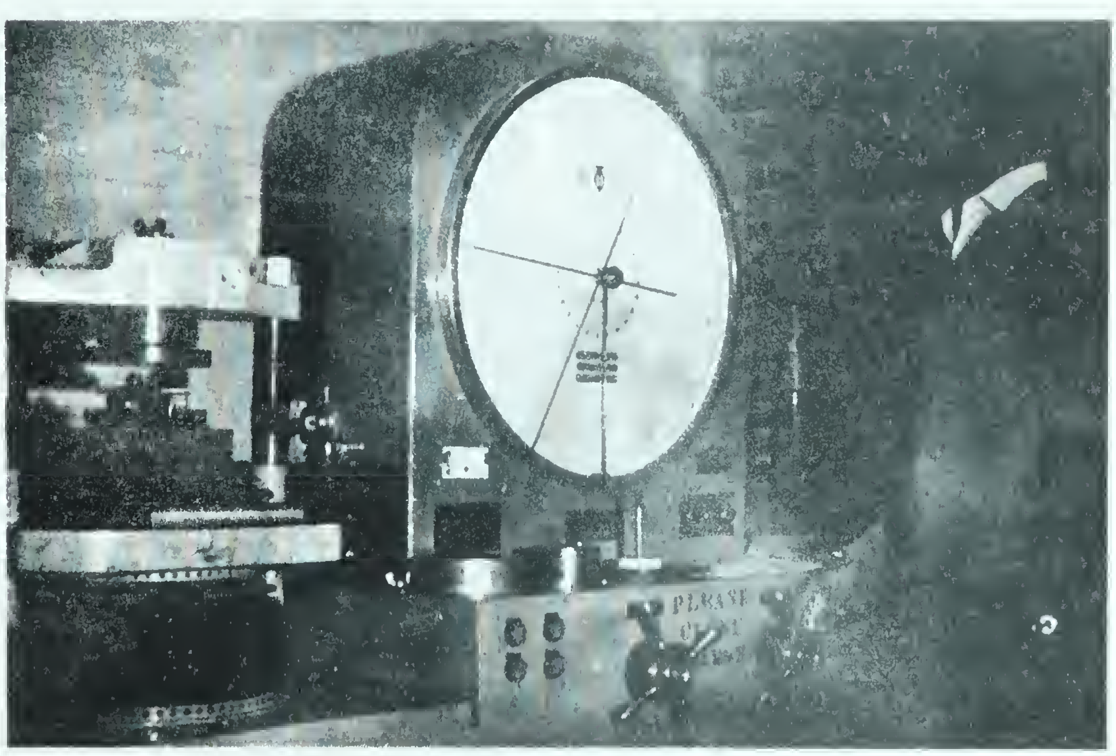
Efforts were made to run the tests at two other frequencies, namely, 500 and 1000 cycles per minute. The tests however, were unsuccessful due to excessive eccentric motion of the mounted test specimens, caused by minor misalignment.

SUMMARY OF TESTS

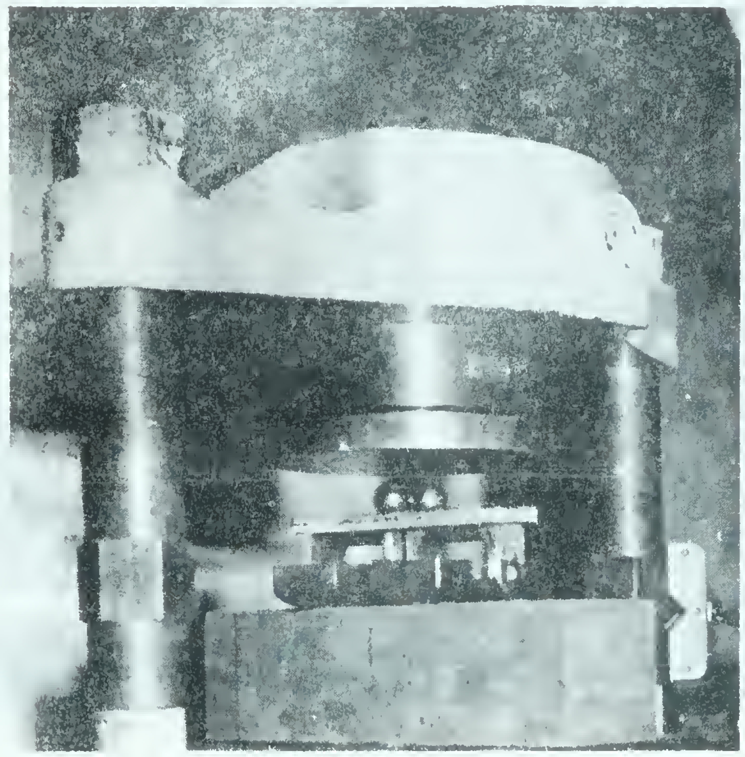
SERIES	Cement Content %	AGE: 3 DAYS				AGE: 14 DAYS			
		Flexure Strength (Beams)	Compressive Strength (Halves)	FATIGUE TEST Stress Level %	FATIGUE TEST No. of Specimen (Cylinders)	Flexure Strength (Beams)	Compressive Strength (Halves)	FATIGUE TEST Stress Level %	FATIGUE TEST No. of Specimen (Cylinders)
ES-6	6	4	8	60 50 40 30 20	5 5 5 4 4	4	8	60 50 40 30 20	4 5 4 5 4
ES-8	8	4	8	60 50 40 30 20	5 5 5 4 2	4	8	60 50 40 30 -	4 5 5 3 -
ES-10	10	4	8	60 50 40 30	4 4 4 2	4	8	60 50 40 30	4 4 3 2



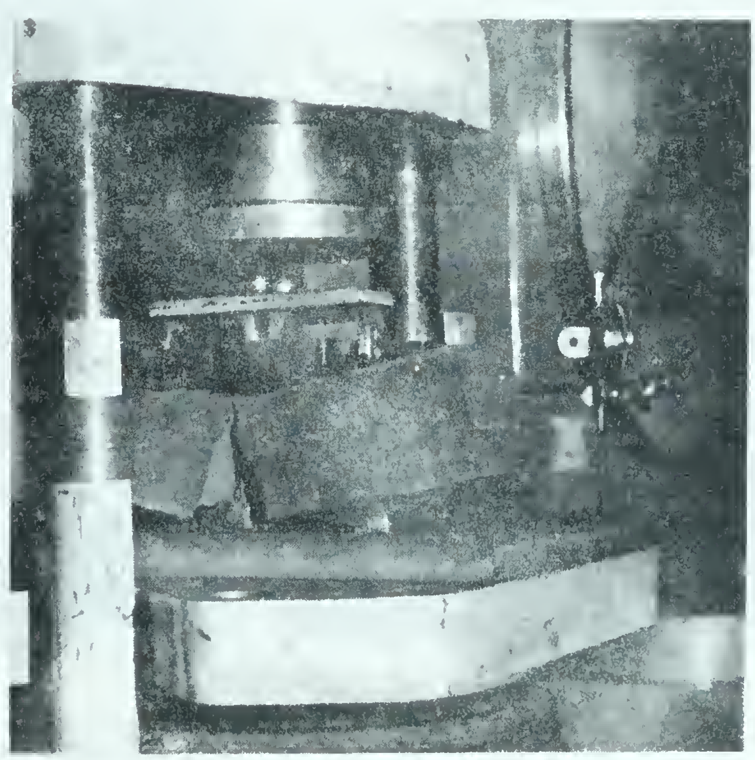
PHOTOGRAPH 1. MOULD FOR FLEXURE TEST BEAMS SHOWING SPECIMEN PALLET AND SPACER FLATS [TOP]



PHOTOGRAPH 2. FLEXURE SPECIMEN PLACED IN TINIUS OLSEN MACHINE FOR TEST.

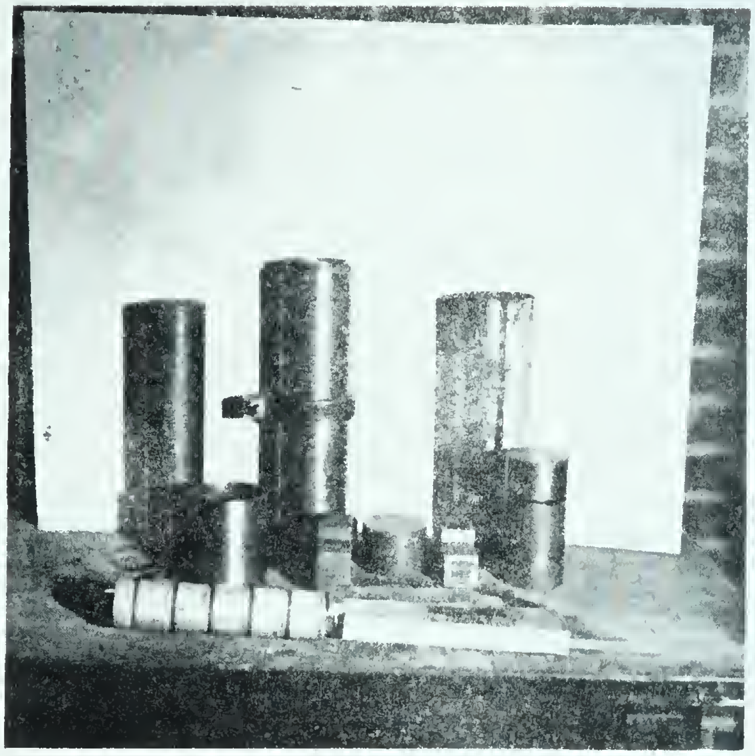


3 [A]

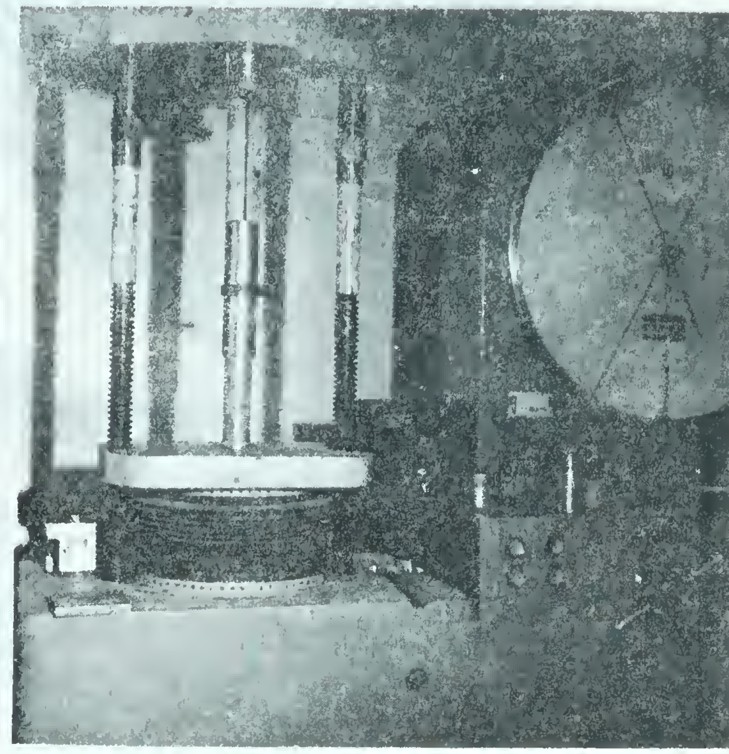


3 [B]

PHOTOGRAPH 3. [A] Enlarged view of loading head
[B] Specimen at failure.

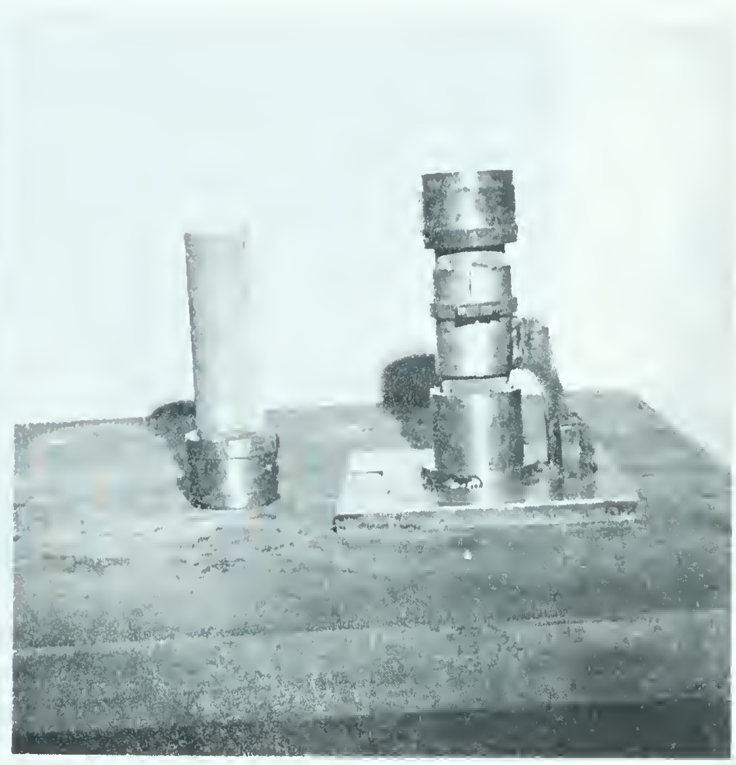


4 [A]



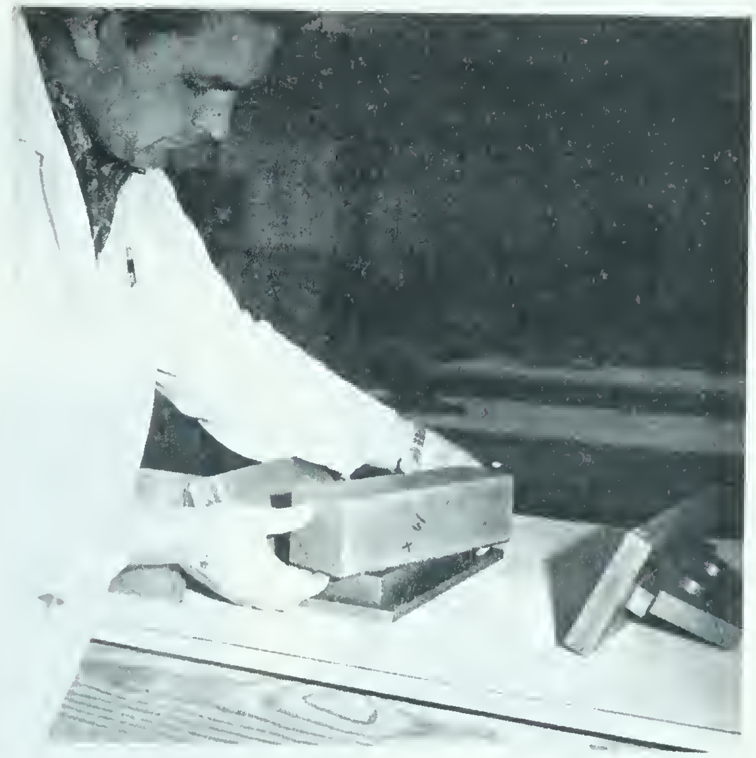
4 [B]

4 [C]



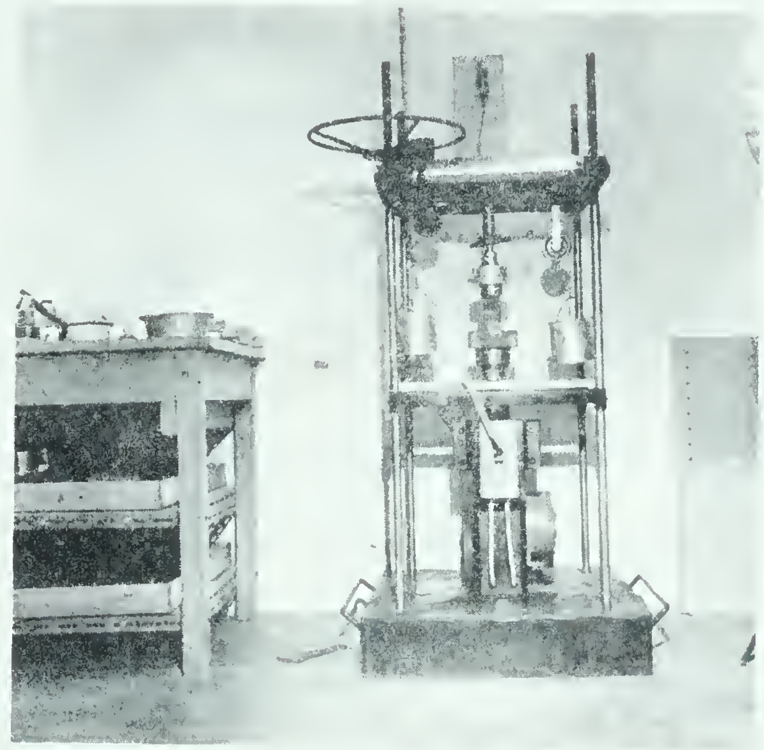
4 [D]

PHOTOGRAPH 4. [A] MOULD FOR FATIGUE TEST SPECIMEN. [B] SPECIMEN BEING EXTRUDED. [C] END PEICES MOUNTING DEVICE. [D] SPECIMEN ON LEFT WITH BOTTOM END PIECE FIXED, ON THE RIGHT SIDE SPECIMEN BEING PROVIDED WITH THE TOP END PIECE.

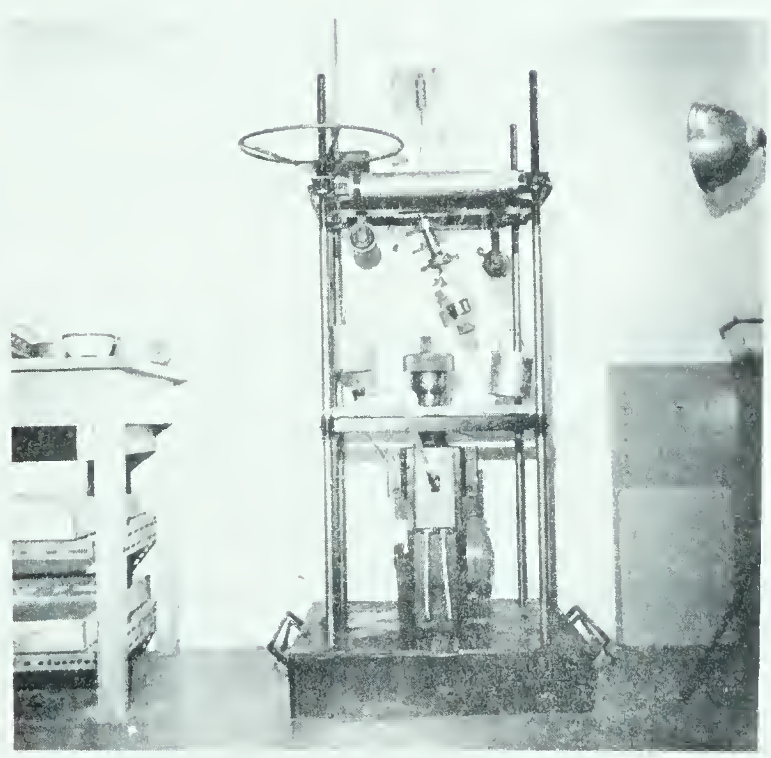


PHOTOGRAPH 5. Fresh flexure test specimen being shifted from the mould base.

PHOTOGRAPH 6. Fatigue test specimen provided with both end pieces.
On the right a fractured specimen.



7 [A]



7 [B]

PHOTOGRAPH 7. CANTILEVER TYPE CONSTANT STRESS AMPLITUDE FATIGUE TESTING MACHINE.

[A]. TEST IN PROGRESS.

[B]. FRACTURED SPECIMEN

CHAPTER V

PRESENTATION AND DISCUSSION OF RESULTS

5.1 Flexure Tests

The results of flexure tests and compression tests are presented in FIGURE 7. This figure is based on a summary of results given in TABLES 4 to 27 of Appendix B.

Each point represents the average value of four flexure tests and eight compression tests of the corresponding half portions of broken specimens. The flexural strength in terms of modulus of rupture increased by about 30 percent in each of the three mixes from 3 days to 14 days age, whereas the compressive strength increased by about 50 percent for the same periods. The relationship between modulus of rupture and compressive strength appears to be curvilinear for this particular sand.

5.2 Fatigue Tests

Three series of specimens were tested for ages of 3 and 14 days, as detailed below. A schedule for loading for different stress levels for the three series is given in TABLE 29 of Appendix C.

The results of the fatigue tests have been presented in FIGURES 8, 9 and 10 in the form of conventional stress vs. number of cycles curves on semi-log plot. Details of the tests are given in TABLES 30 to 35 of Appendix C.

FIGURE 8 shows the S-N curves for 3 and 14 days specimens for six percent mix.

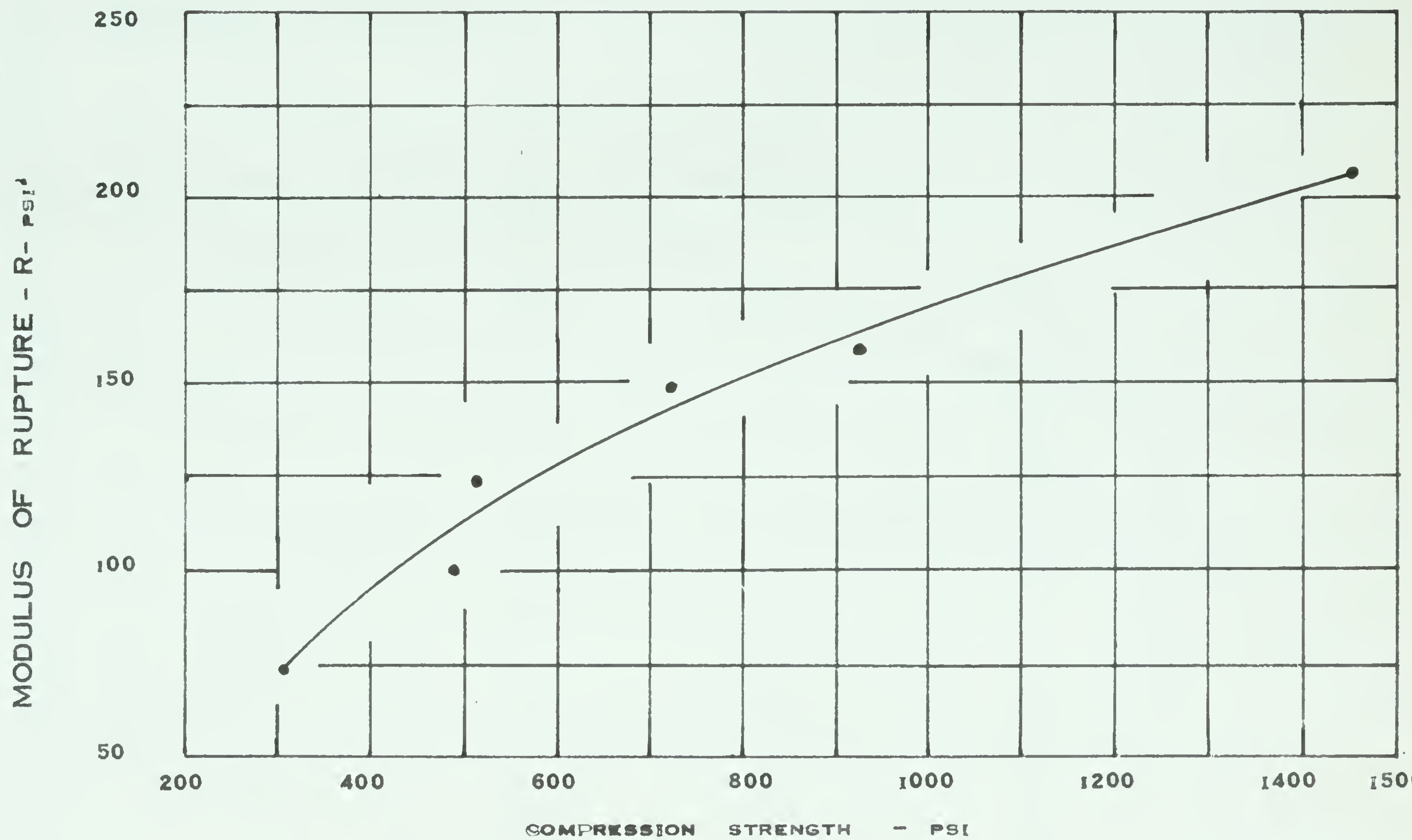


FIGURE 7. RELATION SHIP BETWEEN ULTIMATE COMPRESSION STRENGTH AND MODULUS OF RUPTURE FOR TYPE III CEMENT - SAND MIXES.

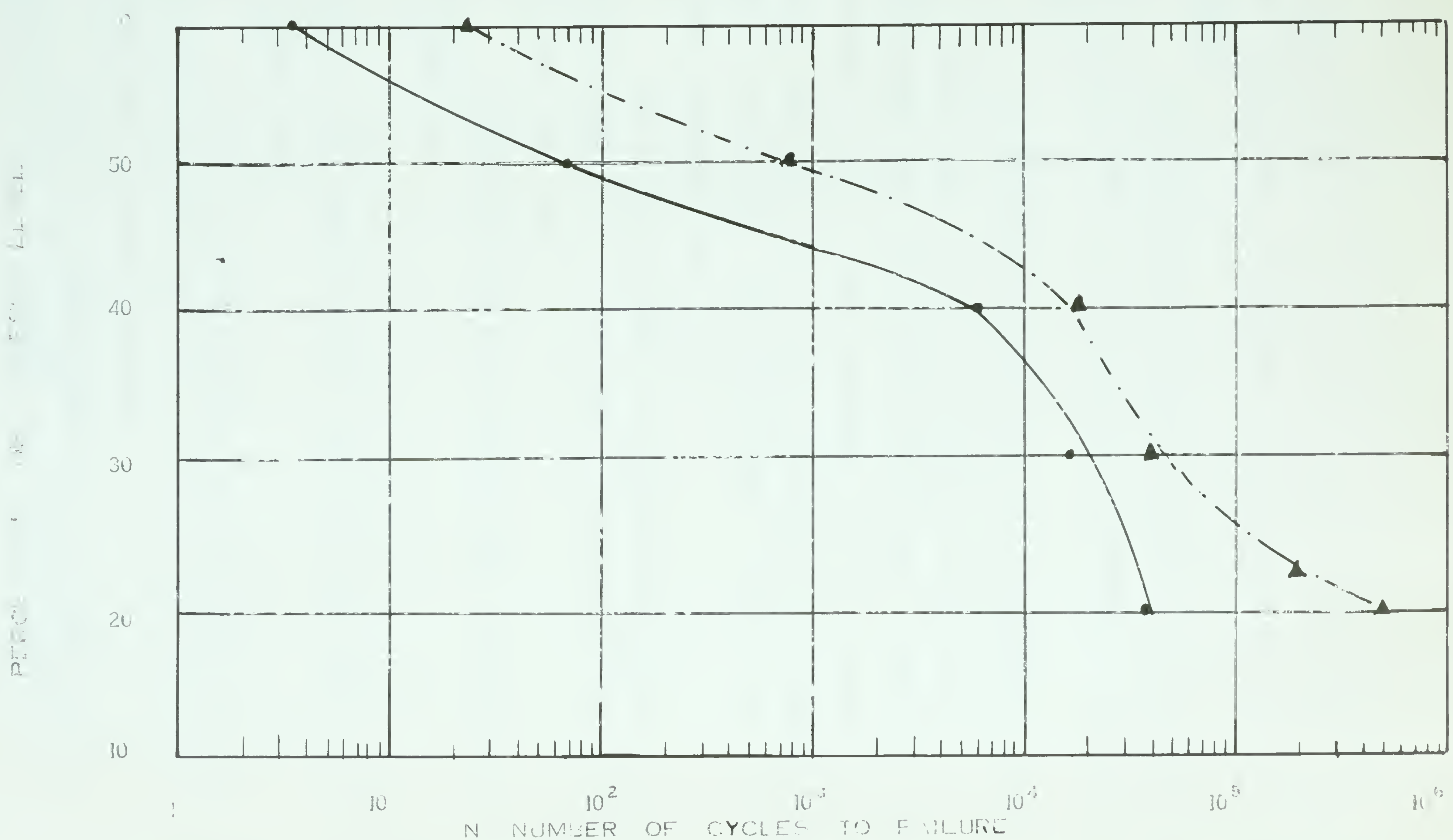


FIGURE 8. FATIGUE RESULTS FOR 6 % TYPE III CEMENT - SAND MIX.

LEGEND. 3 DAYS AGE ——●——●—— 14 DAYS AGE —·—▲—·—▲—·—

Since the modulus of rupture for the 3 day specimens was only 72 psi, it was quite difficult, in the initial stage to run the tests, as many specimens broke while mounting. As handling technique developed, there were only a few breakages.

The maximum number of cycles to failure in this case was 36,421, the average being 34,800. All the specimens failed even at the 20 percent stress level.

A study of the two curves will show that although both the curves have a similar slope between 60 and 40 percent stress levels, they have dissimilar slopes below the 40 percent stress level. In case of 14 days specimens the number of cycles to failure averaged 475,000 at 20 percent stress level. Two more tests were run at a level of 22.5 percent for obtaining an additional point on the S-N curve. The maximum number of cycles in this case was 174,380, the average being 173,650.

Thus in both the ages the specimens did not survive the tests. It therefore appears that the six percent mix experienced early fatigue, even at the lowest stress levels.

FIGURE 9 shows the S-N curves for eight percent mix for the 3 and 14 day specimens.

A study of the two curves indicates identical slope between 60 and 40 percent stress levels for both. Below this level, the two curves deviate in different forms.

In case of 3 days specimens the curve slopes down sharply from 40 to 30 percent level and then levels off gently, for the 20 percent stress level without failure at one million cycles.

In case of 14 days specimens the curve slopes very gently, its form being well defined. The specimens even at stress level of 30 percent did not

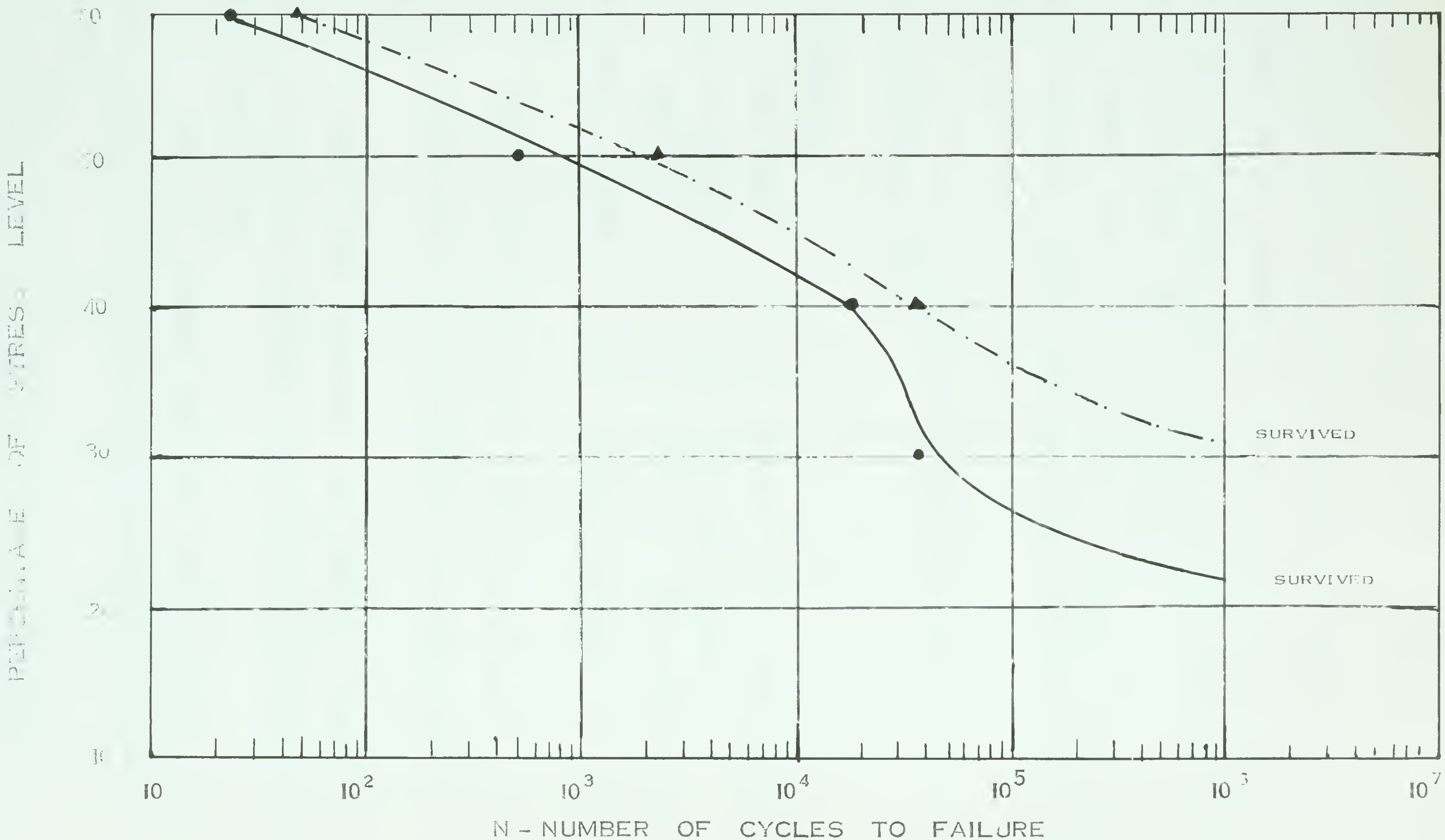


FIGURE 9. FATIGUE RESULTS FOR 8 % TYPE III CEMENT - SAND MIX

LEGEND. 3 DAYS AGE —●——●— 14 DAYS AGE —·—▲—·—

fail at more than one million cycles.

It has been seen that the S-N curves in case of both the 3 days and 14 days ages for six percent mix, and only 3 days age for eight percent mix, bend sharply at 40 percent stress level. For this no reason can be put forward, at this stage, due to insufficient data.

FIGURE 10 shows the S-N curves for ten percent cement-sand mix at 3 and 14 days ages. Both the curves bear great similarity, and are well defined.

In both the cases, the specimens did not fail at one million cycles at 30 percent stress level.

5.3 Discussion

The three sets of curves indicate that the cement stabilized sand does exhibit the effects of fatigue like other materials.

There is an early fatigue failure at higher stresses, and at low stress levels it appears to possess endurance characteristics, though not well defined.

However, as indicated by the curves, the six percent mix is susceptible to quick fatigue in early life, and appears to be a weak material for repeated stresses.

In case of eight percent mix, the behaviour is much better, particularly in fourteen days specimens, which survived one million cycles even at 30 percent stress level.

In case of ten percent mixes both 3 and 14 days specimens behave similarly without much difference, surviving one million cycles at 30 percent stress level.

Refering back to Timoshenko's typical S-N diagrams for ferrous and

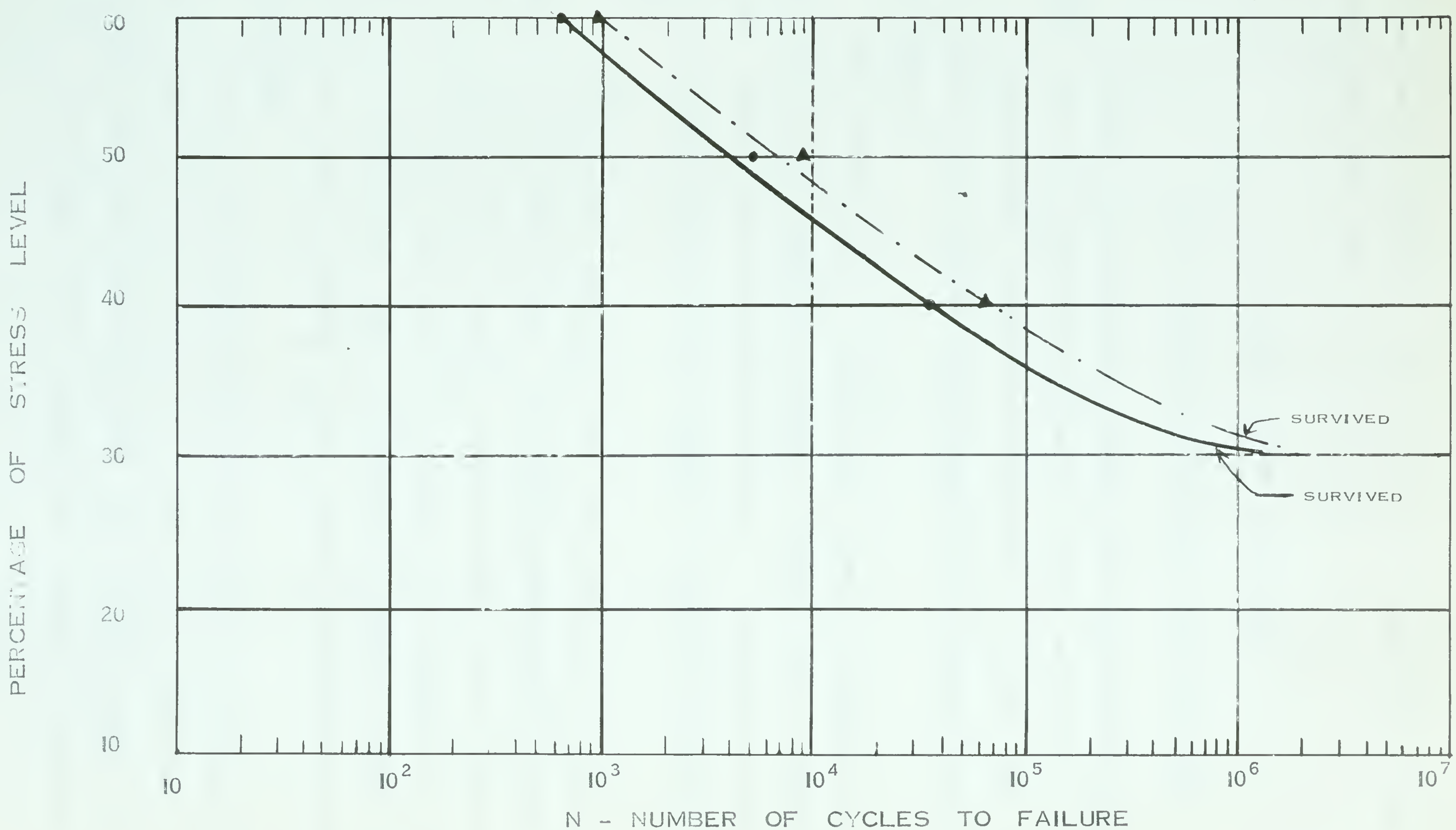


FIGURE 10. FATIGUE RESULTS FOR 10 % TYPE III CEMENT - SAND MIX.

LEGEND. 3 DAYS AGE ——●——●—— 14 DAYS AGE — · ——▲—— · —

non-ferrous metals (FIGURE 1), there appears to be a similarity between S-N curve for non-ferrous metals and the curves for

(i) 8 percent mix at 14 days age.

(ii) 10 percent mix at both 3 and 14 days age.

In case of six percent mix, however, the S-N curves are quite different. This can probably be attributed to little resistance to fatigue.

From an overall comparison of the results, it would appear that under repeated stress reversal, cement stabilized sand exhibits comparable fatigue behaviour.

The S-N diagrams for various series cannot be compared in relation to each other, as the magnitude of stress, at various levels is different in each case, depending upon the modulus of rupture. A comparison, based on values of stresses read from the S-N diagram, is therefore presented in TABLE 2.

A study of this data will reveal that much higher stresses could be applied to the stronger mixes. For instance considering the stresses for N = 10, it increases from 32 psi for 6 percent cement sand at 3 days age to 124 psi for 10 percent cement mix at 14 days age. The increase in stress capacity for stronger mixes might be attributed to change in elastic properties, but further work would be required in this respect to establish the reason for such change.

It may be also mentioned here that the flexure and compressive strengths of Type III cement-sand mix at 3 days age were comparable to 28 days old specimens using normal portland cement. For 14 days specimens, with Type III cement, the strengths could be compared with 3 months old specimens with

TABLE 2

Percentage Cement	Age in Days	Compressive Strength psi	Modulus of Rupture psi R	ALLOWABLE STRESS LEVEL FOR N CYCLES TO FAILURE											
				N=10		$N=10^2$		$N=10^3$		$N=10^4$		$N=10^5$		$N=10^6$	
				%R	psi	%R	psi	%R	psi	%R	psi	%R	psi	%R	psi
6	3	310	72	56	43	49	35	44	32	36	26	-	-	-	-
"	14	495	95	63*	60	55	52	49	47	42	40	26	25	18	17
8	3	515	125	61*	76	55	69	49	61	43	54	27	33	22	27
"	14	730	150	65*	98	58	87	53	80	45	67	36	54	22	33
10	3	930	165			75*	124	58	95	45	74	35	58	30	49
"	14	1460	207			80*	166	60	124	48	100	38	77	31	63

* Values taken by extrapolation

normal portland cement.

It has been shown by other workers that there is a rapid rise in strength in mixes using Type III cement for the first ten days, whereafter, the increase in strength is rather slow.

Thus in case of low stress level tests, for 3 days old specimens, there occurs an increase in strength, which would affect the fatigue test results.

5.4 Effect of Frequency

An effort was made to run the tests at frequencies of 500 and 1000 cycles per minute. But the specimens did not survive even for a few seconds at the lowest stress level. This was probably due to excessive vibrations of the testing machine at high frequencies.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The object of this investigation was to study the fatigue characteristics of cement stabilized sands. As stated in CHAPTER I, this study involves extensive research work and can be expanded to a long term programme. The work covered by the present investigation is thus very limited.

Furthermore only one type of sand has been used, and out of the many variables, only three have been covered, as given below:

(i) Variation in cement percentage.

(ii) Stress level.

(iii) Age.

Based on the results of this investigation the following conclusions may be drawn:

(i) The cement-sand mix does exhibit fairly well defined fatigue characteristics.

(ii) The S-N curves exhibit a similar trend from the 60 to 40 percent stress level for all the three mixes but below this stress level, the relationship is decidedly different.

(iii) The cement-sand mix with high cement ratio appears to have

an endurance limit in the order of 30 percent stress level as calculated in this programme.

(iv) Using the method employed in this investigation, it may be possible to estimate the number of cycles to failure at any particular strength and stress level, for a cement-sand mix for a particular set of variables.

6.2 Recommendations

A considerable number of variables pertaining to fatigue characteristics in cement-sand stabilization warrants further laboratory investigation. The following aspects may be described:-

(i) Attempts should be made to verify and extend the results of this investigation by carrying out tests at stress levels higher and lower than the range adopted in this program.

(ii) Tests should be conducted on other cement-sand mixes, using sands from different sources in order to develop the method of predicting the behaviour of cement-sand mixes under fatigue.

(iii) Tests, using Type III Cement, should be conducted after the period of rapid gain in strength, so that, the effect of increase in strength, during the test, is eliminated.

(iv) The equipment should be modified to eliminate eccentric movements in order to allow high frequency testing.

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APPENDIX A

SAND CLASSIFICATION DATA

- Sieve Analysis.

- Grain Size Curve.

- Moisture-Density Plot for 6, 8 and 10 percent cement sand mixes.

UNIVERSITY of ALBERTA DEP'T. of CIVIL ENGINEERING SOIL MECHANICS LABORATORY **SIEVE ANALYSIS**	PROJECT THESIS SITE KLEIN PIT SAMPLE SAND LOCATION HOLE DEPTH TECHNICIAN MIR DATE 9 9 64

Total Dry Weight of Sample 1337	Sieve No.	Size of Opening Inches	Size of Opening Mm.	Weight Retained gms.	Total Wt. Finer Than gms.	Percent Finer Than	% Finer Than Basis Orig. Sample
Initial Dry Weight Retained No. 4							
Tare No. ______							
Wt. Dry + Tare ______							
Tare ______		3/4	19·10	0	1337	100.0	
Wt. Dry ______		3/8	9·52	0	1337	100 0	
	4	·185	4·76	0.9	1336	99.9	
Passing	4						
Initial Dry Weight							
Passing No. 4	8 ~~10~~	·079	2·000	12.9	1323	99 0	
Tare No. ______	16 ~~20~~	·0331	·840	45 2	1278	95 6	
Wt. Dry + Tare ______	30 ~~40~~	·0165	·420	89 9	1188	88 8	
Tare ______	50 ~~60~~	·0097	·250	669 4	519	38 8	
Wt. Dry ______	100	·0059	·149	340 5	178	13.3	
	200	·0029	·074	92.9	85	6.4	
Passing	200						

Description of Sample ______

Time of Sieving ______

Method of Preparation ______

Remarks ______

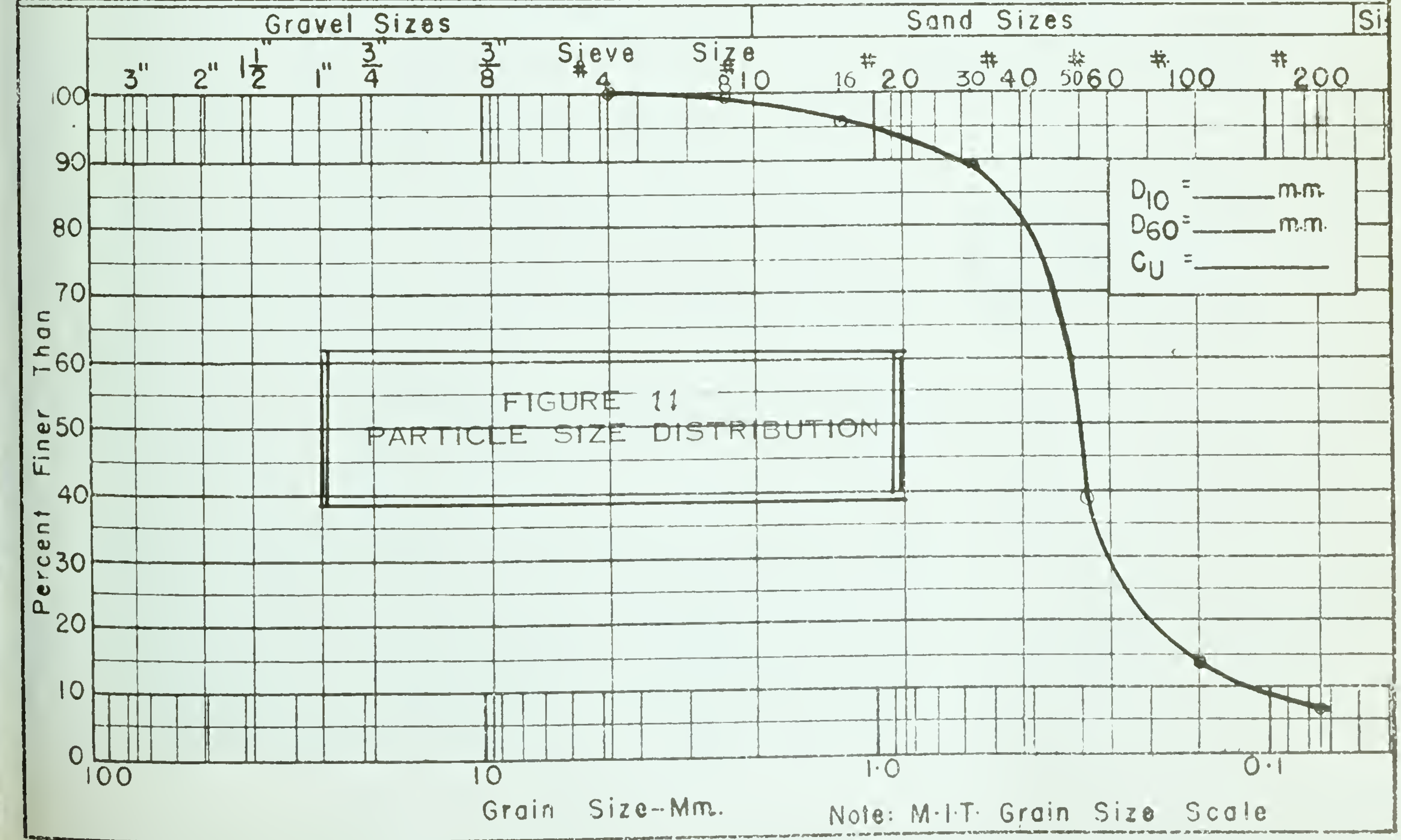
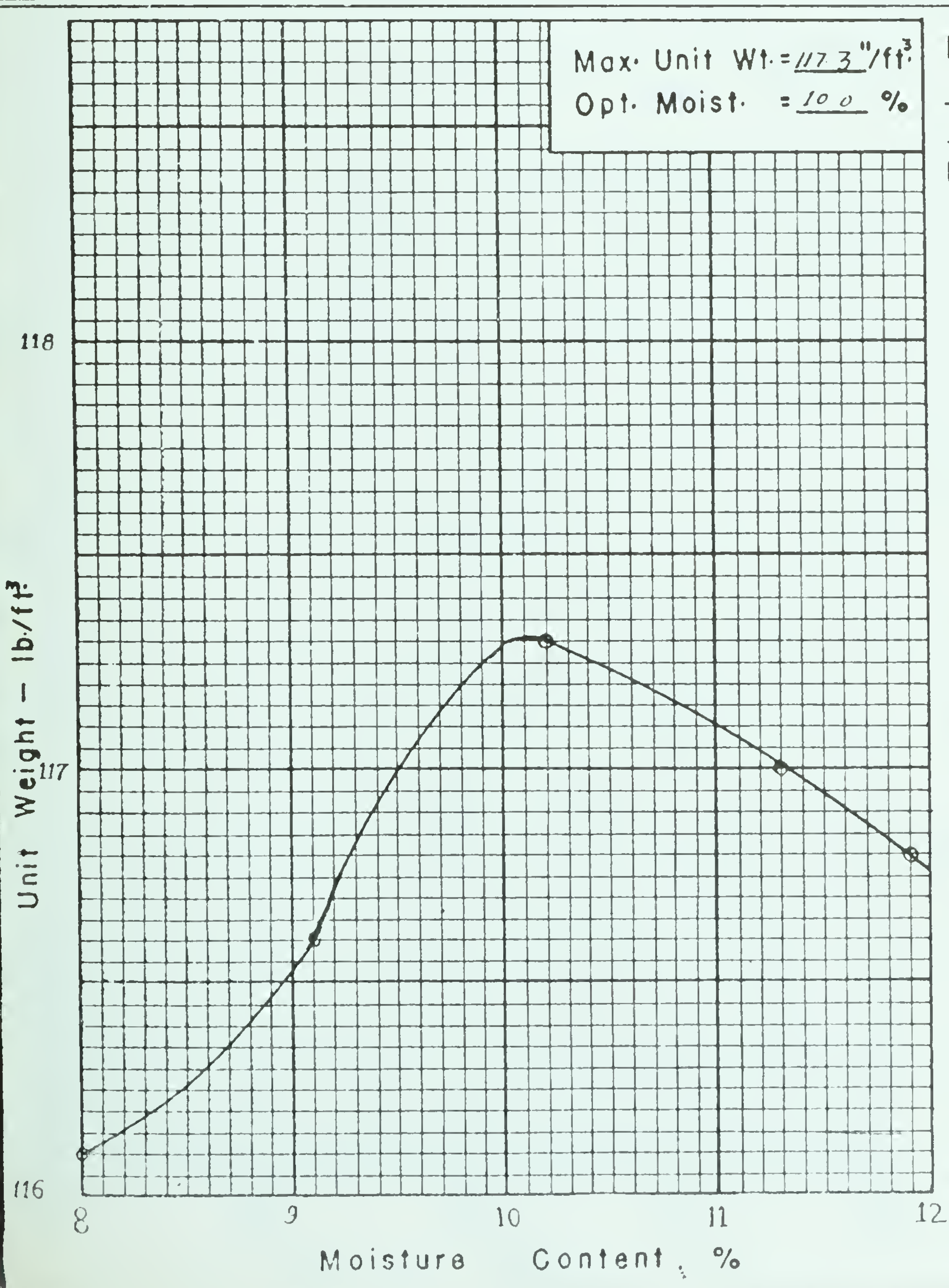


FIGURE 11
PARTICLE SIZE DISTRIBUTION

UNIVERSITY of ALBERTA
DEP'T of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
COMPACTION TEST

PROJECT	THESIS
SITE	KLIEN PIT
SAMPLE	SAND + 6% CEMENT
LOCATION	
HOLE	DEPTH
TECHNICIAN MIR	DATE 5.8.64

Trial Number	1	2	3	4	5		
Unit Weight Determination							
Mold No.							
Wt. Sample Wet + Mold	7178	7202	7242	7250	7239		
Wt. Mold	5279	5279	5279	5279	5279		
Wt. Sample Wet	1899	1923	1963	1971	1960		
Volume Mold	1/30	1/30	1/30	1/30	1/30		
Wet Unit Weight lb/ft^3	125.4	127.2	129.6	130.3	129.5		
Dry Unit Weight lb/ft^3	116.1	116.6	117.3	117.0	116.8		
Moisture Content Determination							
Container No.	A-26	A-40	A-38	A-35	A-8		
Wt. Sample Wet + Tare	185.3	198.1	213.9	207.2	188.0		
Wt. Sample Dry + Tare	173.8	184.2	196.8	189.1	171.1		
Wt. Water	11.5	13.9	17.1	18.1	16.9		
Tare Container	30.1	32.1	29.41	29.8	29.1		
Wt. Dry Soil	143.7	152.1	167.4	159.3	142.0		
Moisture Content	8.0	9.1	10.2	11.3	11.9		



Method of Compaction ______
STANDARD PROCTOR

Diam. Mold ______
Height Mold ______
Volume Mold ______
No. of Layers ______
Blows per Layer ______
Ht. of Free Fall ______
Wt. of Tamper ______
Shape of Tamping Face ______
Description of Sample ______

FIGURE 12

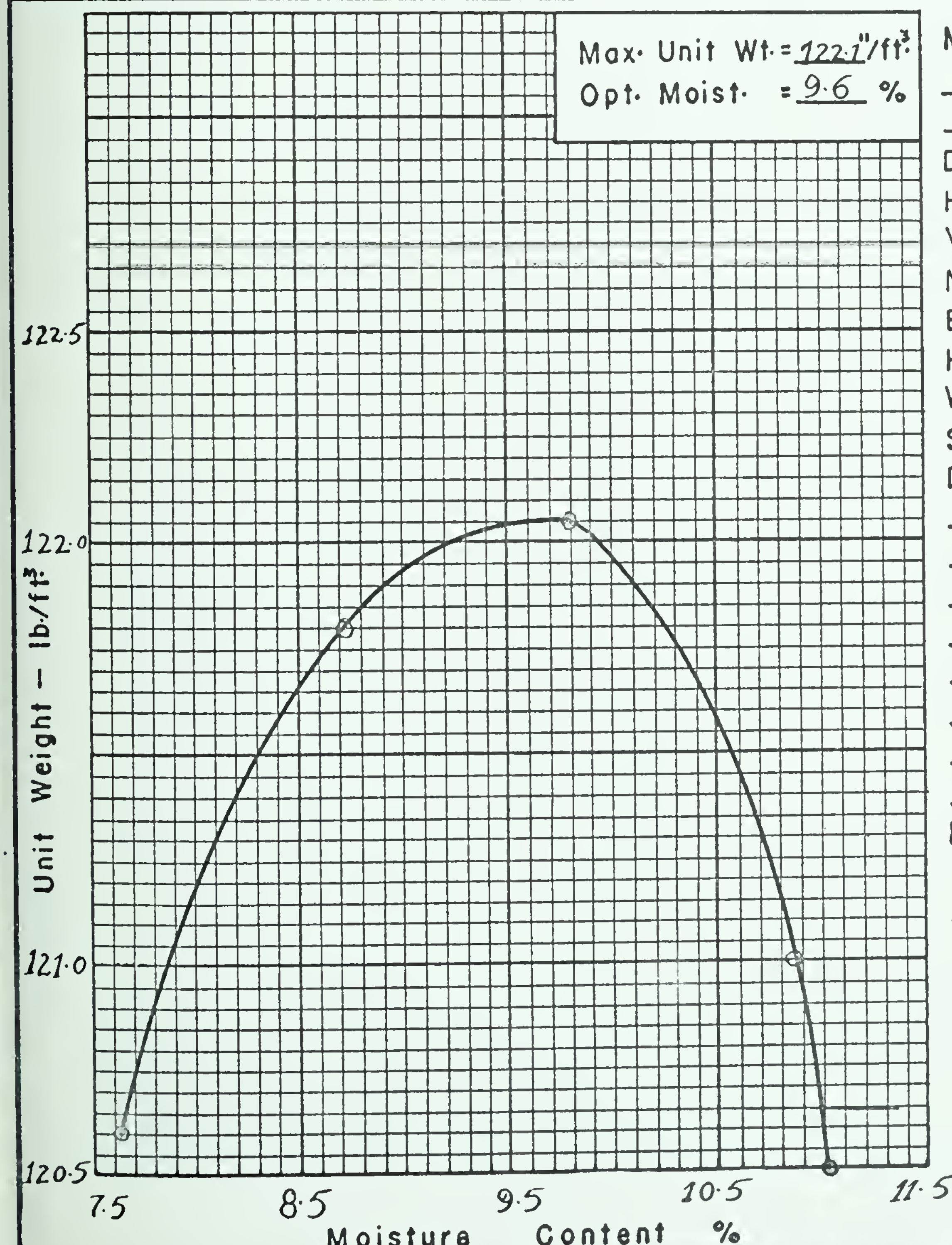
Remarks ______

UNIVERSITY of ALBERTA
DEP'T· of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY

COMPACTION TEST

PROJECT THESIS
SITE KLEIN PIT
SAMPLE SAND + 10% CEMENT
LOCATION
HOLE DEPTH
TECHNICIAN MIR DATE 31. 7. 64

		1	2	3	4	5		
	Trial Number	1	2	3	4	5		
Unit Weight Determination	Mold No·	-	-	-	-	-		
	Wt· Sample Wet + Mold	7242	7277	7302	7302	7300		
	Wt· Mold	5279	5279	5279	5279	5279		
	Wt· Sample Wet	1963	1998	2023	2023	2021		
	Volume Mold	1/30	1/30	1/30	1/30	1/30		
	Wet Unit Weight lb/ft^3	130.0	132.1	134.0	134.0	133.9		
	Dry Unit Weight lb/ft^3	120.6	121.8	122.1	121.0	120.5		
Moisture Content Determination	Container No·	A-7	A-33	R-35	A-1	A-16		
	Wt· Sample Wet + Tare	184.2	197.2	241.2	207.1	211.5		
	Wt· Sample Dry + Tare	173.6	183.9	223.0	190.2	193.7		
	Wt· Water	10.6	13.3	18.2	16.9	17.8		
	Tare Container	34.7	30.4	35.4	34.2	32.6		
	Wt· Dry Soil	138.9	152.5	187.6	156.0	161.1		
	Moisture Content	7.63	8.72	9.80	10.84	11.1		



Method of Compaction PROCTOR

Diam. Mold
Height Mold
Volume Mold
No· of Layers
Blows per Layer
Ht· of Free Fall
Wt· of Tamper
Shape of Tamping Face
Description of Sample

FIGURE 14.

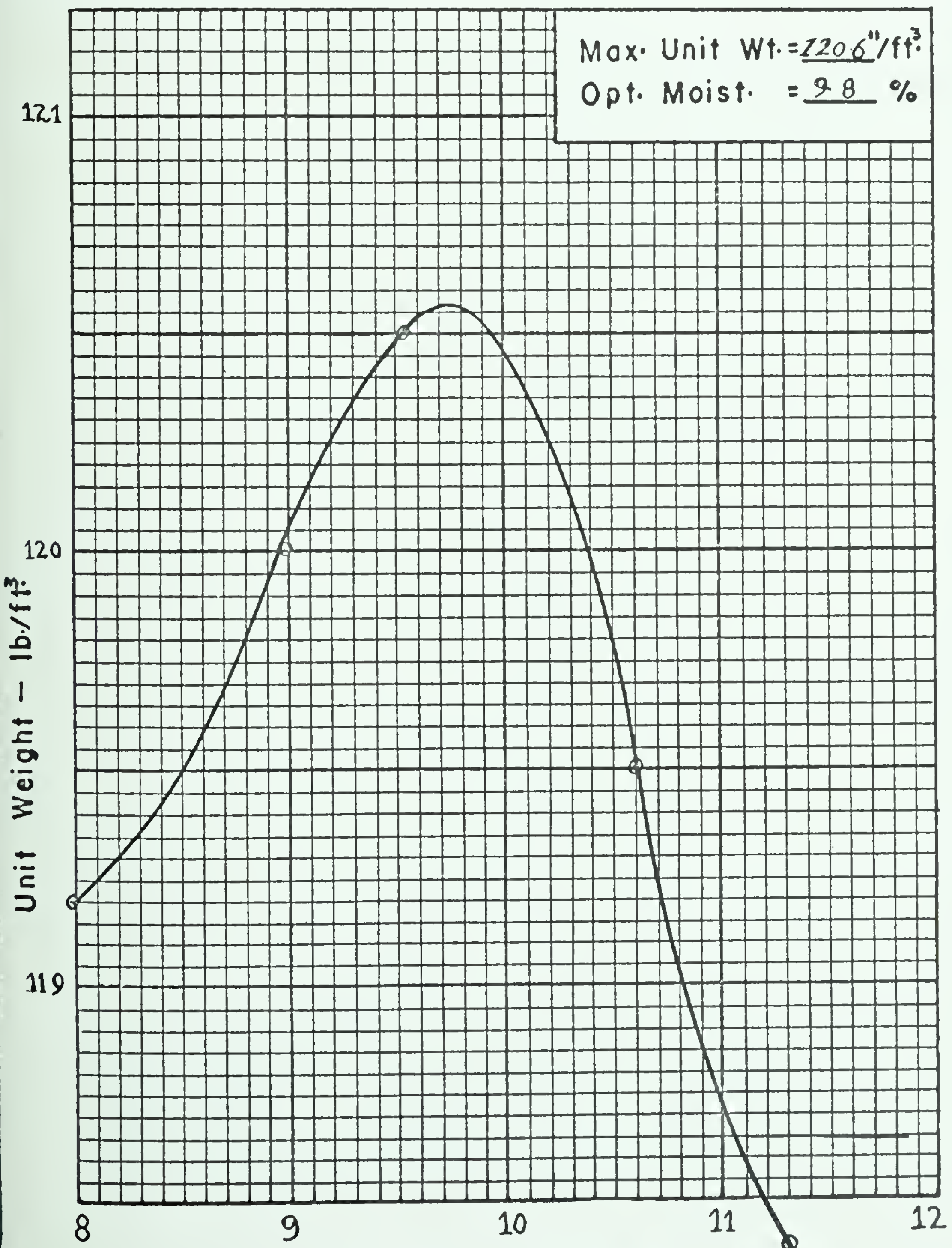
Remarks

UNIVERSITY of ALBERTA
DEP'T. of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
COMPACTION TEST

PROJECT THESIS
SITE KLEIN PIT
SAMPLE SAND + 8 % CEMENT
LOCATION
HOLE DEPTH
TECHNICIAN MIR DATE 31. 7. 64

	Trial Number	1	2	3	4	5		
Unit Weight Determination	Mold No.	"	"	"	"	"		
	Wt. Sample Wet + Mold	7224	7252	7276	7279	7277		
	Wt. Mold	5279	5279	5279	5279	5279		
	Wt. Sample Wet	1945	1973	1997	2000	1998		
	Volume Mold	1/30	1/30	1/30	1/30	1/30		
	Wet Unit Weight lb./ft.^{3}	128.8	130.5	132.0	132.1	132.0		
	Dry Unit Weight lb./ft.^{3}	119.2	120.0	120.5	119.5	118.4		
Moisture Content Determination	Container No.	R-14	R-13	R-6	R-1	A-17		
	Wt. Sample Wet + Tare	235.0	229.2	229.0	268.0	248.0		
	Wt. Sample Dry + Tare	220.2	213.1	212.1	245.5	225.2		
	Wt. Water	14.8	16.1	16.9	22.5	21.8		
	Tare Container	34.9	33.5	34.9	32.9	31.7		
	Wt. Dry Soil	185.3	179.6	177.2	212.6	193.5		
	Moisture Content	7.99	8.96	9.54	10.6	11.3		

Max. Unit Wt. = 120.6 lb/ft^3
Opt. Moist. = 9.8 %



Method of Compaction PROCTOR

Diam. Mold
Height Mold
Volume Mold
No. of Layers
Blows per Layer
Ht. of Free Fall
Wt. of Tamper
Shape of Tamping Face
Description of Sample

FIGURE 13.

Remarks

APPENDIX B

FLEXURE AND COMPRESSION TESTS

- Detailed Procedure of A.S.T.M. Methods No. D1632-D1635 of 1963.
- Detailed Data for Flexure and Compression Tests.

Moulding of flexure specimen was done according to A.S.T.M. Method No. D1632-D1635 of 1963 with the exception that a minor modification was introduced to facilitate the removal of the specimens, from the mould.

In the original A.S.T.M. Method the fresh specimen is transferred to a glass plate by turning around the base through 90°. This is quite a cumbersome procedure as lot of weight of the base is involved and considerable effort is required resulting in breakages. To eliminate this, the longer sides of the moulds were provided with additive 3/16" spacer strips on the top and a 3/16" plate of the size 2-31/32" x 11-17/32" was introduced at the bottom, that is, on the top of the base. When the specimen was compacted, and mould opened, it could be removed right on the pallet itself (Photographs 1 and 5). Eight pallets were required for each set of testing.

Exact weight of the dry mix required according to dry density was taken and mixed with the amount of water as per optimum moisture, for each percentage of cement. Sample calculations have been shown in TABLE 3.

The wet mix was then placed in the mould in three equal layers, using 90 blows of 5/8" diameter 18" long tamping rod, for each layer, without compaction but to the point of refusal.

The top was then placed and the whole mould was placed on the platen of Tinius Olson Machine to apply static load to the extent that designed volume was achieved. The load was held for 20 seconds before releasing to counteract the rebound.

The mould was then removed from the Compression Machine and opened out. The specimen was taken away to be kept in the lab room till evening, covered up with plastic sheet to avoid excessive drying. The set of specimens was then placed in the Moisture room with relative humidity of 100% and

temperature of 73°F. for the required period of curing.

Flexure Test

Flexure tests were conducted according to A.S.T.M. Method No. D1632 and D1635 of 1963. This requires the use of two point loading head and a set of roller and rocker supports (Photograph 3), along with a base plate. The base plate was placed on the platen of Tinius Olson Compression Machine and specimen was placed with the compaction side along the depth after marking out the 9" span and middle third portion on the bearings (Photographs 2 and 3).

Over the specimen was placed the loading head with two 3/4" diameter steel balls on top, for transmission of load to the specimen.

The rate of displacement of the platen was swt at 0.05" per minute and load applied till fracture.

The loading at the instance of fracture was recorded, specimen was removed from the compression machine. Breadth and depth were noted from both sides of the fracture.

TABLE No. 4 to 15 indicate the results of the flexure tests using Type III Cement and TABLES No. 16 to 27 show the results of preliminary tests using the Type I, Normal Portland Cement.

Compression Tests

The next step was to perform the compression tests on the portions of fractured beams as per A.S.T.M. Method No. D1634 - 63.

These results have been shown in above referred tables.

TABLE 3.

SAMPLE CALCULATIONS
FOR
FLEXURE TESTS

SIZE OF SPECIMEN 3" X 3" — 11.25"
VOLUME OF SPECIMEN = .059 CFT

NO	CEMENT CONTENT	DESIGN DENSITY LBS / CFT	OPTIMUM MOISTURE	WT. OF MIX GM	WT. OF SAND GM	WT. OF CEMENT GM	WT. OF WATER GM
1	6%	117.3	10%	3128	2950	178	313
2	8%	120.6	9 8%	3230	2990	239	323
3	10%	122.1	9 6%	3280	2980	300	315

RESEARCH PROJECT FOR CYCLIC LOADING ON SOIL CEMENT

FLEXURE TEST ON CEMENT SOIL SPECIMENS

(ASTM Method No. D1632 and D1635 - 63)

TABLE 4.

SPECIMEN IDENTIFICATION NO: ES 6-A
SOURCE: KLEIN PIT
GRADATION
DESIGN DATA: MOISTURE CONTENT 10 % DENSITY 117.3 CEMENT CONTENT 6 %
DETAILS OF CURING: MOISTURE ROOM 100% R.H.
DATE OF CASTING 8. 9. 64. DATE OF TESTING 11. 9. 64. AGE 3 DAYS
LOAD HEAD WEIGHT: - 2.745 kgm.

ENGINEER: MIR

Serial No.	Load Reading Initial	Load Reading Final	Net P (kgm)	Dimensions (inches)	b	d	Position of crack	Modulus of Rupture = R psi
1.	7.00	105.00	100.745	i.	3.084	3.049	MIDDLE THIRD	70
				ii.	3.086	3.052		
				iii.	3.098	3.050		
				iv.	3.096	3.049		
				Avge.	3.091	3.050		
2.	6.5	115.00	111.245	i.	3.080	3.054	"	76.5
				ii.	3.079	3.052		
				iii.	3.088	3.056		
				iv.	3.082	3.058		
				Avge.	3.082	3.055		
3.	7.5	106.00	101.245	i.	3.092	3.052	"	70
				ii.	3.091	3.052		
				iii.	3.095	3.067		
				iv.	3.089	3.064		
				Avge.	3.092	3.059		
4.	7.00	125.00	120.745	i.	3.081	3.059	"	82
				ii.	3.085	3.060		
				iii.	3.079	3.067		
				iv.	3.085	3.068		
				Avge.	3.083	3.063		AVG. = 72

Modulus of Rupture for crack within the middle-third is given by the Equation $R = \frac{P \times Length}{b \times d^2}$ in psi

COMPRESSIVE STRENGTH OF SOIL-CEMENT USING

PORTIONS OF BEAMS BROKEN IN FLEXURE

(ASTM Method No. D1634 - 63)

TABLE 5.

SPECIMEN IDENTIFICATION NO: ES6-A

SOURCE: KLEIN PIT. AGE 3 DAYS. CURING: MOISTURE ROOM

Serial No.	Specimen Portion	Dimensions inches	Area Sq. inches	Total Load P (kgm)	fc in psi $= \frac{P \times 2.2}{Area}$
1	(i)	3.110 x 3.05	9.48	1300	300
	(ii)	3.085 x 3.057	9.43	1350	315
2	(i)	3.1 x 3.05	9.45	1340	310.
	(ii)	3.053 x 3.074	9.384	1200	285
3	(i)	3.055 x 3.063	9.48	1370	315
	(ii)	3.058 x 3.106	9.5	1377	310
4	(i)	3.062 x 3.059	9.427	1360	320
	(ii)	3.053 x 3.10	9.464	1470	330

RESEARCH PROJECT FOR CYCLIC LOADING ON SOIL CEMENT

FLEXURE TEST ON CEMENT SOIL SPECIMENS

(ASTM Method No. D1632 and D1635 - 63)

SPECIMEN IDENTIFICATION NO: ES-6-B　　　　TABLE 6.

SOURCE: KLEIN PIT　　　　GRADATION

DESIGN DATA:　　MOISTURE CONTENT 10 %　　DENSITY 117.3　　CEMENT CONTENT 6 %

DETAILS OF CURING: MOISTURE ROOM 100% R.H

DATE OF CASTING 8. 9. 64　　DATE OF TESTING 22. 9. 64.　　AGE 14 DAYS

LOAD HEAD WEIGHT: - 2.745 kgm.

ENGINEER: M I R

Serial No.	Load Reading Initial	Load Reading Final	Net P (kgm)	Dimensions (inches)	b	d	Position of crack	Modulus of Rupture = R psi
1.	12.8	146.00	136.545	i.	3.082	3.052	MIDDLE THIRD	94
				ii.	3.084	3.053		
				iii.	3.096	3.062		
				iv.	3.102	3.058		
				Avge.	3.090	3.056		
2.	10.5	148.50	140.745	i.	3.084	3.063	"	95
				ii.	3.091	3.065		
				iii.	3.089	3.063		
				iv.	3.090	3.064		
				Avge.	3.088	3.074		
3.	12.0	152.00	142.745	i.	3.057	3.049	"	98
				ii.	3.065	3.048		
				iii.	3.052	3.047		
				iv.	3.050	3.045		
				Avge.	3.056	3.048		
4.	9.0	143.00	136.745	i.	3.061	3.052	"	95
				ii.	3.058	3.047		
				iii.	3.066	3.066		
				iv.	3.064	3.059		
				Avge.	3.062	3.056		AVG. = 95

Modulus of Rupture for crack within the middle-third is given by the Equation $R = \frac{2.2 \times P \times \text{Length}}{b \times d^2}$ in psi

COMPRESSIVE STRENGTH OF SOIL-CEMENT USING

PORTIONS OF BEAMS BROKEN IN FLEXURE

(ASTM Method No. D1634 - 63)

TABLE 7.

SPECIMEN IDENTIFICATION NO: ES6-B.

SOURCE: KLEIN PIT. AGE 14 DAYS CURING: MOISTURE ROOM

Serial No.	Specimen Portion	Dimensions inches	Area Sq. inches	Total Load P (kgm)	fc in psi $= \frac{P \times 2.2}{Area}$
1	(i)	3.05 × 3.1	9.455	1980	460
	(ii)	3.048 × 3.097	9.439	2050	480
2	(i)	3.055 × 3.088	9.433	2280	530
	(ii)	3.088 × 3.052	9.424	2070	485
3	(i)	3.065 × 3.053	9.357	2145	505
	(ii)	3.040 × 3.065	9.317	2240	540
4	(i)	3.041 × 3.058	9.30	1845	440
	(ii)	3.057 × 3.087	9.436	2180	510

FLEXURE TEST ON CEMENT SOIL SPECIMENS

(ASTM Method No. D1632 and D1635 - 63)

TABLE 8.

SPECIMEN IDENTIFICATION NO: ES-8-A
SOURCE: KLEIN PIT
DESIGN DATA: GRADATION MOISTURE CONTENT 9.8 % DENSITY 120.6 CEMENT CONTENT 8 %
DETAILS OF CURING: MOISTURE ROOM 100 % R.H
DATE OF CASTING 30.9.64. DATE OF TESTING 3 10.64 AGE 3 DAYS
LOAD HEAD WEIGHT: - 2.745 kgm.

ENGINEER: MIR

Serial No.	Load Reading Initial	Load Reading Final	Net P (Kgm)	Dimensions (inches)	b	d	Position of crack	Modulus of Rupture = R psi
1.	8.75	196.00	189.995	i.	3.065	3.066	MIDDLE THIRD	132
				ii.	3.067	3.067		
				iii.	3.065	3.050		
				iv.	3.065	3.050		
				Avge.	3.065	3.056		
2.	8.00	187.00	179.745	i.	3.05	3.061	"	121
				ii.	3.05	3.050		
				iii.	3.05	3.075		
				iv.	3.05	3.075		
				Avge.	3.05	3.065		
3.	5.75	176.00	173.995	i.	3.025	3.035	"	124
				ii.	3.030	3.037		
				iii.	3.025	3.035		
				iv.	3.025	3.029		
				Avge.	3.026	3.034		
4.	6.00	186.00	182.745	i.	3.067	3.055	"	126
				ii.	3.065	3.055		
				iii.	3.075	3.063		
				iv.	3.075	3.065		
				Avge.	3.070	3.059		AVG. = 125

Modulus of Rupture for crack within the middle-third is given by the Equation $R = \frac{P \times \text{Length} \times 2.2}{b \times d^2}$ in psi

COMPRESSIVE STRENGTH OF SOIL-CEMENT USING

PORTIONS OF BEAMS BROKEN IN FLEXURE

(ASTM Method No. D1634 - 63)

TABLE 9.

SPECIMEN IDENTIFICATION NO: ES8-A

SOURCE: KLEIN PIT

AGE 3 DAYS.

CURING: MOISTURE ROOM

Serial No.	Specimen Portion	Dimensions inches	Area Sq. inches	Total Load P (kgm)	fc in psi $= \frac{P \times 2.2}{Area}$
1	(i)	3.049 x 3.089	9.418	2326	545
	(ii)	3.063 x 3.060	9.372	2175	510
2	(i)	3.075 x 3.060	9.41	2165	505
	(ii)	3.037 x 3.050	9.263	2010	477
3	(i)	3.029 x 3.029	9.174	2239	535
	(ii)	3.024 x 3.042	9.20	2167	520
4	(i)	3.073 x 3.035	9.326	2280	540
	(ii)	3.065 x 3.080	9.44	2105	490

RESEARCH PROJECT FOR CYCLIC LOADING ON SOIL CEMENT

FLEXURE TEST ON CEMENT SOIL SPECIMENS

(ASTM Method No. D1632 and D1635 - 63)

TABLE 10.

SPECIMEN IDENTIFICATION NO: ES 8- B.
SOURCE: KLEIN PIT.
GRADATION
DESIGN DATA: MOISTURE CONTENT 9.8 % DENSITY 120.6. CEMENT CONTENT 8 %
DETAILS OF CURING: MOISTURE ROOM 100 % R.H
DATE OF CASTING 1. 10. 64. DATE OF TESTING 15. 10. 64. AGE 14 DAYS
LOAD HEAD WEIGHT: - 2.745 kgm.

ENGINEER: MIR

Serial No.	Load Reading Initial	Load Reading Final	Net P (Kgm)	Dimensions (inches)	b	d	Position of crack	Modulus of Rupture = R psi
1.	9.0	222.0	215.745	i.	3.067	3.070	MIDDLE THIRD	148
				ii.	3.065	3.068		
				iii.	3.060	3.075		
				iv.	3.061	3.072		
				Avge.	3.063	3.071		
2.	8.5	218.5	215.745	i.	3.087	3.053	"	147
				ii.	3.083	3.052		
				iii.	3.094	3.053		
				iv.	3.088	3.053		
				Avge.	3.088	3.053		
3.	5.0	222.0	219.745	i.	3.075	3.045	"	153
				ii.	3.075	3.045		
				iii.	3.071	3.043		
				iv.	3.075	3.048		
				Avge.	3.074	3.045		
4.	6.00	215.0	211.745	i.	3.068	3.041	"	149
				ii.	3.062	3.045		
				iii.	3.071	3.051		
				iv.	3.070	3.049		
				Avge.	3.067	3.056		AVG = 150

Modulus of Rupture for crack within the middle-third is given by the Equation $R = \frac{P \times Length \times 2.2}{b \times d^2}$ in psi

COMPRESSIVE STRENGTH OF SOIL-CEMENT USING

PORTIONS OF BEAMS BROKEN IN FLEXURE

(ASTM Method No. D1634 - 63)

TABLE II.

SPECIMEN IDENTIFICATION NO: E58 B.

SOURCE: KLEIN PIT

AGE 14 DAYS

CURING: MOISTURE ROOM

Serial No.	Specimen Portion	Dimensions inches	Area Sq. inches	Total Load P (kgm)	fc in psi $= \frac{P \times 2.2}{Area}$
1	(i)	3.078 × 3.053	9.397	2980	700
	(ii)	3.084 × 3.048	9.40	3160	740
2	(i)	3.113 × 3.035	9.447	2808	655
	(ii)	3.073 × 3.076	9.452	3190	755
3	(i)	3.073 × 3.025	9.295	3100	715
	(ii)	3.097 × 3.088	9.563	3330	785
4	(i)	3.066 × 3.044	9.332	3120	735
	(ii)	3.070 × 3.050	9.363	3080	725

FLEXURE TEST ON CEMENT SOIL SPECIMENS

(ASTM Method No. D1632 and D1635 - 63)

TABLE 12.

SPECIMEN IDENTIFICATION NO: ES-10-A.
SOURCE: KLEIN PIT
GRADATION
DESIGN DATA: MOISTURE CONTENT 9.6 % DENSITY 122.1 CEMENT CONTENT 10 %
DETAILS OF CURING: MOISTURE ROOM. 100 % R.H
DATE OF CASTING 19.10.64. DATE OF TESTING 22.10.64. AGE 3 DAYS.
LOAD HEAD WEIGHT: - 2.745 kgm.

ENGINEER: MIR

Serial No.	Load Reading Initial	Load Reading Final	Net P (Kgm)	Dimensions (inches)	b	d	Position of crack	Modulus of Rupture = R psi
1.	6.00	245.50	242.245	i.	3.070	3.071	MIDDLE THIRD.	173
				ii.	3.071	3.067		
				iii.	3.075	3.068		
				iv.	3.073	3.068		
				Avge.	3.072	3.068		
2.	5.50	238.50	235.745	i.	3.093	3.072	"	160
				ii.	3.100	3.075		
				iii.	3.105	3.067		
				iv.	3.105	3.068		
				Avge.	3.100	3.073		
3.	7.00	235.00	230.745	i.	3.080	3.072	"	162
				ii.	3.083	3.069		
				iii.	3.075	3.070		
				iv.	3.083	3.062		
				Avge.	3.080	3.068		
4.	6.00	240.00	236.745	i.	3.069	3.082	"	164
				ii.	3.068	3.081		
				iii.	3.071	3.079		
				iv.	3.072	3.080		
				Avge.	3.070	3.080		AVG = 165

Modulus of Rupture for crack within the middle-third is given by the Equation $R = \frac{P \times \text{Length} \times 2.2}{b \times d^2}$ in psi

COMPRESSIVE STRENGTH OF SOIL-CEMENT USING

PORTIONS OF BEAMS BROKEN IN FLEXURE

(ASTM Method No. D1634 - 63)

TABLE 13.

SPECIMEN IDENTIFICATION NO: E S10 A

SOURCE: KLEIN PIT.   AGE 3 DAYS.   CURING: MOISTURE ROOM.

Serial No.	Specimen Portion	Dimensions inches	Area Sq. inches	Total Load P (kgm)	fc in psi $= \frac{P \times 2.2}{Area}$
1	(i)	3.07 x 3.069	9.449	4100	954
	(ii)	3.074 x 3.068	9.431	3925	915
2	(i)	3.097 x 3.073	9.517	4018	930
	(ii)	3.10 x 3.069	9.513	3961	916
3	(i)	3.081 x 3.070	9.458	3974	925
	(ii)	3.082 x 3.069	9.453	4080	950
4	(i)	3.080 x 3.068	9.450	3895	905
	(ii)	3.070 x 3.081	9.458	4027	940

FLEXURE TEST ON CEMENT SOIL SPECIMENS

(ASTM Method No. D1632 and D1635 - 63)

TABLE 14.

SPECIMEN IDENTIFICATION NO: ES-10-B.
SOURCE: KLEIN PIT
GRADATION
DESIGN DATA: MOISTURE CONTENT 9.6 % DENSITY 122.1 CEMENT CONTENT 10 %
DETAILS OF CURING: MOISTURE ROOM 100 % R.H.
DATE OF CASTING 19.10.64. DATE OF TESTING 2.11.64. AGE 14 DAYS
LOAD HEAD WEIGHT: - 2.745 kgm.

ENGINEER: M I R

Serial No.	Load Reading Initial	Load Reading Final	Net P (Kgm)	Dimensions (inches)	b	d	Position of crack	Modulus of Rupture = R psi
1.	7.00	304.00	299.745	i.	3.085	3.062	MIDDLE THIRD.	205
				ii.	3.085	3.055		
				iii.	3.083	3.058		
				iv.	3.083	3.059		
				Avge.	3.084	3.058		
2.	6.00	301.00	297.745	i.	3.078	3.062	"	205
				ii.	3.078	3.071		
				iii.	3.082	3.052		
				iv.	3.077	3.055		
				Avge.	3.079	3.060		
3.	7.00	313.00	308.745	i.	3.075	3.075	"	210
				ii.	3.075	3.075		
				iii.	3.075	3.082		
				iv.	3.075	3.083		
				Avge.	3.075	3.079		
4.	6.00	299.745		i.	3.067	3.071	"	207
				ii.	3.068	3.073		
				iii.	3.058	3.072		
				iv.	3.058	3.070		
				Avge.	3.063	3.071.		AVG. = 207

Modulus of Rupture for crack within the middle-third is given by the Equation $R = \frac{P \times Length \times 2.2}{b \times d^2}$ in psi

COMPRESSIVE STRENGTH OF SOIL-CEMENT USING

PORTIONS OF BEAMS BROKEN IN FLEXURE

(ASTM Method No. D1634 - 63)

TABLE 15.

SPECIMEN IDENTIFICATION NO: E 5-10-B

SOURCE: KLEIN PIT AGE 14 DAYS CURING: MOISTURE ROOM.

Serial No.	Specimen Portion	Dimensions inches	Area Sq. inches	Total Load P (kgm)	fc in psi $= \frac{P \times 2.2}{Area}$
1	(i)	3.049 x 3.090	9.42	6350	1485
	(ii)	3.05 x 3.090	9.45	6250	1460
2	(i)	3.070 x 3.650	9.35	6050	1425
	(ii)	3.10 x 3.050	9.50	6070	1410
3	(i)	3.087 x 3.080	9.69	6520	1480
	(ii)	3.085 x 3.068	9.50	6550	1520
4	(i)	3.068 x 3.073	9.42	6110	1430
	(ii)	3.058 x 3.070	9.40	6200	1450

RESEARCH PROJECT FOR CYCLIC LOADING ON SOIL CEMENT

FLEXURE TEST ON CEMENT SOIL SPECIMENS

(ASTM Method No. D1632 and D1635 - 63)

TABLE 16.

SPECIMEN IDENTIFICATION NO: K-1-A
SOURCE: KLEIN PIT
GRADATION
DESIGN DATA: MOISTURE CONTENT 10% DENSITY 117.3 CEMENT CONTENT 6 %
DETAILS OF CURING: MOISTURE ROOM 100% R.H.
DATE OF CASTING 17.7.64. DATE OF TESTING 24.7.64. AGE 7 DAYS
LOAD HEAD WEIGHT: - 2.745 kgm.

ENGINEER: MIR

Serial No.	Load Reading Initial	Load Reading Final	Net P (kgm)	Dimensions (inches)	b	d	Position of crack	Modulus of Rupture = R psi
1.	15.00	75.00	62.745	i.	3.030	3.025	MIDDLE THIRD	45
				ii.	3.025	3.025		
				iii.	3.030	3.0125		
				iv.	3.025	3.01		
				Avge.	3.0275	3.018		
2.	10.5	81.00	73.245	i.	3.025	3.020	"	53
				ii.	3.030	3.00		
				iii.	3.030	3.00		
				iv.	3.025	3.0125		
				Avge.	3.0275	3.008		
3.	10.00	84.00	76.245	i.	3.05	3.03	"	54
				ii.	3.05	3.025		
				iii.	3.06	3.0125		
				iv.	3.05	3.03		
				Avge.	3.052	3.0243		
4.	7.00	72.00	67.745	i.	3.05	3.05	"	48
				ii.	3.025	3.03		
				iii.	3.025	3.05		
				iv.	3.03	3.025		
				Avge.	3.031	3.039		AVG = 50 psi

Modulus of Rupture for crack within the middle-third is given by the Equation $R = \frac{P \times L \ldots \times 2.2}{b \times d}$ in psi

COMPRESSIVE STRENGTH OF SOIL-CEMENT USING

PORTIONS OF BEAMS BROKEN IN FLEXURE

(ASTM Method No. D1634 - 63)

TABLE 17.

SPECIMEN IDENTIFICATION NO: K-1-A

SOURCE: KLEIN PIT. AGE 7-DAYS CURING: MOISTURE ROOM.

Serial No.	Specimen Portion	Dimensions inches	Area Sq. inches	Total Load P (kgm)	fc in psi $= \frac{P \times 2.2}{Area}$
1	(i)	3.03 x 3.022	9.156	1540	370
	(ii)	3.022 x 3.012	9.102	1430	345
2	(i)	3.028 x 3.015	9.129	1470	355
	(ii)	3.020 x 3.00	9.06	1380	335
3	(i)	3.049 x 3.03	9.238	1450	345
	(ii)	3.058 x 3.022	9.241	1400	335
4	(i)	3.047 x 3.048	9.287	1500	355
	(ii)	3.032 x 3.038	9.211	1440	345

RESEARCH PROJECT FOR CYCLIC LOADING ON SOIL CEMENT

FLEXURE TEST ON CEMENT SOIL SPECIMENS

(ASTM Method No. D1632 and D1635 - 63)

TABLE 18.

SPECIMEN IDENTIFICATION NO: K-1-B
SOURCE: KLEIN PIT
GRADATION
DESIGN DATA: MOISTURE CONTENT 10 % DENSITY 117.3 CEMENT CONTENT 6 %
DETAILS OF CURING: MOISTURE ROOM 100% R.H.
DATE OF CASTING 28.7.64 DATE OF TESTING 24.8.64. AGE 28 DAYS
LOAD HEAD WEIGHT: - 2.745 kgm.

ENGINEER: MIR

Serial No.	Load Reading Initial	Load Reading Final	Net P (Kgm)	Dimensions (inches)	b	d	Position of crack	Modulus of Rupture = R psi
1.	12.00	114.5	105.245	i.	3.052	3.055	MIDDLE THIRD	73
				ii.	3.054	3.053		
				iii.	3.049	3.053		
				iv.	3.052	3.051		
				Avge.	3.052	3.053		
2.	12.00	117.6	107.245	i.	3.055	3.055	"	74
				ii.	3.053	3.053		
				iii.	3.051	3.051		
				iv.	3.048	3.052		
				Avge.	3.052	3.052		
3.	11.00	113.0	104.745	i.	3.054	3.052	"	73
				ii.	3.055	3.052		
				iii.	3.064	3.055		
				iv.	3.066	3.055		
				Avge.	3.060	3.053		
4.	8.00	114.0	108.745	i.	3.058	3.054	"	75
				ii.	3.057	3.053		
				iii.	3.063	3.055		
				iv.	3.063	3.054		
				Avge.	3.060	3.054		AVG = 73.75

Modulus of Rupture for crack within the middle-third is given by the Equation $R = \frac{P \times Length \times 2.2}{b \times d^2}$ in psi

COMPRESSIVE STRENGTH OF SOIL-CEMENT USING

PORTIONS OF BEAMS BROKEN IN FLEXURE

(ASTM Method No. D1634 - 63)

TABLE 19.

SPECIMEN IDENTIFICATION NO: K-1 B

SOURCE: KLEIN PIT AGE 28 DAYS. CURING: MOISTURE ROOM

Serial No.	Specimen Portion	Dimensions inches	Area Sq. inches	Total Load P (kgm)	fc in psi $= \frac{P \times 2.2}{Area}$
1	(i)	3.05 x 3.065	9.325	2140	505
	(ii)	3.040 x 3.075	9.30	2180	515
2	(i)	3.038 x 3.061	9.29	1965	470
	(ii)	3.053 x 3.048	9.30	2185	520
3	(i)	3.077 x 3.055	9.46	1990	465
	(ii)	3.039 x 3.053	9.26	1895	450
4	(i)	3.071 x 3.043	9.32	2165	510
	(ii)	3.048 x 3.058	9.30	2130	505

FLEXURE TEST ON CEMENT SOIL SPECIMENS

(ASTM Method No. D1632 and D1635 - 63)

SPECIMEN IDENTIFICATION NO: K-2-A

TABLE 20.

SOURCE: KLEIN PIT

GRADATION

DESIGN DATA: MOISTURE CONTENT 9.8 % DENSITY 120.6 CEMENT CONTENT 8 %

DETAILS OF CURING: MOISTURE ROOM 100 % R.H.

DATE OF CASTING 6. 8. 64 DATE OF TESTING 13. 8. 64. AGE 7 DAYS.

LOAD HEAD WEIGHT: - 2.745 kgm.

ENGINEER: MIR

Serial No.	Load Reading Initial	Load Reading Final	Net P (kgm)	Dimensions (inch)	b	d	Position of crack	Modulus of Rupture = R psi
1.	12.00	169.00	159.745	i.	3.116	3.079	MIDDLE THIRD.	107
				ii.	3.126	3.080		
				iii.	3.124	3.079		
				iv.	3.103	3.080		
				Avge.	3.111	3.079		
2.	11.50	161.5	152.745	i.	3.095	3.075	"	103
				ii.	3.094	3.079		
				iii.	3.083	3.079		
				iv.	3.087	3.079		
				Avge.	3.089	3.078		
3.	12.5	170.00	160.245	i.	3.090	3.125	"	105
				ii.	3.092	3.131		
				iii.	3.096	3.122		
				iv.	3.095	3.123		
				Avge.	3.093	3.125		
4.	12.5	165.00	155.245	i.	3.100	3.094	"	104
				ii.	3.100	3.087		
				iii.	3.115	3.080		
				iv.	3.105	3.080		
				Avge.	3.105	3.085		AVG. = 104.75

Modulus of Rupture for crack within the middle-third is given by the Equation $R = \frac{P \times Length \times 2.2}{b \times d^2}$ in psi

COMPRESSIVE STRENGTH OF SOIL-CEMENT USING

PORTIONS OF BEAMS BROKEN IN FLEXURE

(ASTM Method No. D1634 - 63)

TABLE 21.

SPECIMEN IDENTIFICATION NO: K-2-A

SOURCE: KLEIN PIT. AGE 7 DAYS CURING: MOISTURE ROOM

Serial No.	Specimen Portion	Dimensions inches	Area Sq. inches	Total Load P (kgm)	fc in psi $= \frac{P \times 2.2}{Area}$
1	(i)	3.122 × 3.080	9.615	2345	535
	(ii)	3.104 × 3.079	9.557	1900	435
2	(i)	3.095 × 3.079	9.529	2200	510
	(ii)	3.086 × 3.074	9.486	1880	430
3	(i)	3.094 × 3.128	9.671	2130	530
	(ii)	3.096 × 3.126	9.684	2230	505
4	(i)	3.110 × 3.094	9.622	2260	520
	(ii)	3.100 × 3.080	9.548	2240	520

FLEXURE TEST ON CEMENT SOIL SPECIMENS

(ASTM Method No. D1632 and D1635 - 63)

TABLE 22.

SPECIMEN IDENTIFICATION NO: K-2-B.
SOURCE: KLEIN PIT
GRADATION
DESIGN DATA: MOISTURE CONTENT 9.8 % DENSITY 120.6 CEMENT CONTENT 8 %
DETAILS OF CURING: MOISTURE ROOM 100 % R.H.
DATE OF CASTING 6.8.64. DATE OF TESTING 3.9.64 AGE 28 DAYS
LOAD HEAD WEIGHT: - 2.745 kgm.

ENGINEER: MIR

Serial No.	Load Reading Initial	Load Reading Final	Net P (Kgm)	Dimensions (inches)	b	d	Position of crack	Modulus of Rupture = R psi
1.	9.00	203.00	196.745	i.	3.105	3.097	MIDDLE THIRD	133
				ii.	3.103	3.111		
				iii.	3.114	3.075		
				iv.	3.125	3.080		
				Avge.	3.112	3.091		
2.	9.00	200.00	193.745	i.	3.084	3.075	"	135
				ii.	3.086	3.075		
				iii.	3.089	3.068		
				iv.	3.089	3.069		
				Avge.	3.087	3.072		
3.	8.5	201.00	195.245	i.	3.068	3.089	"	132
				ii.	3.078	3.088		
				iii.	3.067	3.094		
				iv.	3.071	3.095		
				Avge.	3.071	3.091		
4.	8.5	202.00	196.245	i.	3.084	3.062	"	134
				ii.	3.078	3.068		
				iii.	3.077	3.058		
				iv.	3.071	3.058		
				Avge.	3.085	3.061		AVG. = 133

Modulus of Rupture for crack within the middle-third is given by the Equation $R = \frac{P \times Length \times 2.2}{b \times d^2}$ in psi

COMPRESSIVE STRENGTH OF SOIL-CEMENT USING

PORTIONS OF BEAMS BROKEN IN FLEXURE

(ASTM Method No. D1634 - 63)

TABLE 23.

SPECIMEN IDENTIFICATION NO: K-2-B.

SOURCE: KLEIN PIT.   AGE 28 DAYS   CURING: MOISTURE ROOM

Serial No.	Specimen Portion	Dimensions inches	Area Sq. inches	Total Load P (kgm)	fc in psi $= \frac{P \times 2.2}{Area}$
1	(i)	3.093 x 3.083	9.535	3975	920
	(ii)	3.080 x 3.140	9.671	3800	865
2	(i)	3.096 x 3.086	9.554	4080	940
	(ii)	3.094 x 3.063	9.476	3820	885
3	(i)	3.102 x 3.068	9.516	3730	890
	(ii)	3.079 x 3.078	9.477	3800	880
4	(i)	3.068 x 3.075	9.437	3400	800
	(ii)	3.070 x 3.045	9.348	3840	900.

FLEXURE TEST ON CEMENT SOIL SPECIMENS

(ASTM Method No. D1632 and D1635 - 63)

SPECIMEN IDENTIFICATION NO: K-3-A. TABLE 24.
SOURCE: GRADATION
DESIGN DATA: MOISTURE CONTENT 9.6 % DENSITY 122.1 CEMENT CONTENT 10 %
DETAILS OF CURING:
DATE OF CASTING 10.8.64 DATE OF TESTING 17.8.64. AGE 7 DAYS
LOAD HEAD WEIGHT: - 2.745 kgm.

ENGINEER: MIR

Serial No.	Load Reading Initial	Load Reading Final	Net P (Kgm)	Dimensions (inches)	b	d	Position of crack	Modulus of Rupture = R psi
1.	10.00	180.00	172.745	i.	3.054	3.061	MIDDLE THIRD	120
				ii.	3.059	3.065		
				iii.	3.059	3.046		
				iv.	3.056	3.047		
				Avge.	3.057	3.055		
2.	7.00	181.00	176.745	i.	3.083	3.043	"	122
				ii.	3.083	3.043		
				iii.	3.061	3.039		
				iv.	3.088	3.042		
				Avge.	3.079	3.042		
3.	9.00	178.00	171.745	i.	3.065	3.050	"	119
				ii.	3.071	3.050		
				iii.	3.067	3.055		
				iv.	3.057	3.065		
				Avge.	3.065	3.055		
4.	10.00	182.00	173.745	i.	3.055	3.060	"	120
				ii.	3.062	3.063		
				iii.	3.059	3.057		
				iv.	3.059	3.055		
				Avge.	3.060	3.059		AVG: = 120.25

Modulus of Rupture for crack within the middle-third is given by the Equation $R = \frac{P \times Length \times 2.2}{b \times d^2}$ in psi

COMPRESSIVE STRENGTH OF SOIL-CEMENT USING

PORTIONS OF BEAMS BROKEN IN FLEXURE

(ASTM Method No. D1634 - 63)

TABLE 25.

SPECIMEN IDENTIFICATION NO: K-3-A.

SOURCE: KLEIN PIT AGE 7 DAYS CURING: MOISTURE ROOM

Serial No.	Specimen Portion	Dimensions inches	Area Sq. inches	Total Load P (kgm)	fc in psi $= \frac{P \times 2.2}{Area}$
1	(i)	3.041 x 3.068	9.33	2800	660
	(ii)	3.048 x 3.051	9.29	2740	650
2	(i)	3.096 x 3.045	9.427	2940	685
	(ii)	3.025 x 3.025	9.15	2830	680
3	(i)	3.680 x 3.047	9.38	2800	660
	(ii)	3.083 x 3.065	9.45	2870	670
4	(i)	3.058 x 3.062	9.381	2790	655
	(ii)	3.061 x 3.058	9.36	2840	670

FLEXURE TEST ON CEMENT SOIL SPECIMENS

(ASTM Method No. D1632 and D1635 - 63)

TABLE 26.

SPECIMEN IDENTIFICATION NO: K-3-B
SOURCE: KLEIN PIT
GRADATION
DESIGN DATA: MOISTURE CONTENT 9.6 % DENSITY 122.1 CEMENT CONTENT 10 %
DETAILS OF CURING: MOISTURE ROOM 100 % R.H.
DATE OF CASTING 11.8.64 DATE OF TESTING 7.9.64 AGE 28 DAYS.
LOAD HEAD WEIGHT: - 2.745 kgm.

ENGINEER: MIR

Serial No.	Load Reading		Net P (Kgm)	Dimensions (inches)			Position of crack	Modulus of Rupture = R psi
	Initial	Final			b	d		
1.	10.00	274.00	264.745	i.	3.071	3.055	MIDDLE THIRD	183
				ii.	3.067	3.059		
				iii.	3.077	3.046		
				iv.	3.078	3.050		
				Avge.	3.073	3.052		
2.	6.50	261.66	256.845	i.	3.059	3.046	"	178
				ii.	3.055	3.050		
				iii.	3.059	3.054		
				iv.	3.060	3.055		
				Avge.	3.058	3.051		
3.	7.50	262.00	257.245	i.	3.091	3.049	"	178
				ii.	3.085	3.047		
				iii.	3.087	3.051		
				iv.	3.084	3.051		
				Avge.	3.087	3.049		
4.	9.00	255.00	248.745	i.	3.070	3.065	"	170
				ii.	3.071	3.077		
				iii.	3.078	3.071		
				iv.	3.072	3.075		
				Avge.	3.073	3.072		AVG. = 175

Modulus of Rupture for crack within the middle-third is given by the Equation $R = \frac{P \times Length \times 2.2}{b \times d^2}$ in psi

COMPRESSIVE STRENGTH OF SOIL-CEMENT USING

PORTIONS OF BEAMS BROKEN IN FLEXURE

(ASTM Method No. D1634 - 63)

TABLE 27.

SPECIMEN IDENTIFICATION NO: K-3-B.

SOURCE: KLEIN PIT. AGE 28 DAYS CURING: MOISTURE ROOM.

Serial No.	Specimen Portion	Dimensions inches	Area Sq. inches	Total Load P (kgm)	fc in psi $= \frac{P \times 2.2}{Area}$
1	(i)	3.065 x 3.062	9.385	4620	1085
	(ii)	3.067 x 3.034	9.323	4685	1105
2	(i)	3.067 x 3.042	9.329	4700	1110
	(ii)	3.076 x 3.050	9.381	5400	1266
3	(i)	3.122 x 3.045	9.50	4930	1140
	(ii)	3.040 x 3.054	9.284	4400	1042
4	(i)	3.056 x 3.075	9.39	4660	1095
	(ii)	3.062 x 3.083	9.44	4675	1090

APPENDIX C

FATIGUE TEST DATA

SAMPLE CALCULATIONS	TABLE 28
SCHEDULE OF LOADING	TABLE 29
SUMMARY OF FATIGUE TEST RESULTS	TABLE 30 to 35

TABLE 28.

SAMPLE CALCULATIONS FOR FATIGUE TESTS

SIZE OF SPECIMEN : 2" DIAMETER X 8" LENGTH

SERL. NO.	CEMENT CONTENT	DESIGN DENSITY	OPTIMUM MOISTURE %	WT. OF DRY MIX GM	WT. OF SAND GM	WT. OF CEMENT GM	WT. OF WATER GM
1	6%	117.3	10	774	730	43.2	77.4
2	8%	120.6	9.8	796	737	59.0	78.0
3	10%	122.1	9.6	805	733	733	77.3

TABLE 29.

SCHEDULE OF LOADING
FOR
FATIGUE TESTS

$W = FD^3/45.75$; FOR $D = 1.9''$ AND $A = 4.5''$ $W = 68F$ IN GRAMMES

SERL. NO.	SPECIMEN SERIES	R PSI	STRESS LEVEL 60%		STRESS LEVEL 50%		STRESS LEVEL 40%		STRESS LEVEL 30%		STRESS LEVEL 20%	
			R PSI	W GM	R PSI	W GM	R PSI	W GM	R PSI	W GM	R PSI	W GM
1	ES-6-A	72	43.0	2925	36.0	2437	28.8	1950	21.5	1462	14.4	975
2	ES6-B	95	57.5	3925	47.5	3270	38.0	2616	28.75	1962	19.0	1308
3	ES8-A	125	65.0	4420	62.5	4017	50.0	3614	32.5	2210	25.0	1807
4	ES8-B	150	90.0	6120	75.0	5100	60.0	4080	45.0	3060	30.0	2040
5	ES10-A	165	99.0	6730	82.5	5610	66.0	4486	49.5	3365	33.0	2243
6	ES10-B	207	124.0	8430	103.5	7025	82.8	5620	62.1	4215	41.4	2810

TABLE 30.

SUMMARY OF FATIGUE TESTS RESULTS

FREQUENCY- 100 C PM

SERIES ES6 AGE 3 DAYS

R = MODULUS OF RUPTURE = 72 PSI

STRESS LEVEL							AVERAGE N
60 %	SPECIMEN NO.	1	2	12	23	31	23
	N	BROKE	3	BROKE	2	2	
50 %	SPECIMEN NO.	13	24	32	33	39	73
	N	72	82	68	70	73	
40 %	SPECIMEN NO.	3	4	14	25	40	6170
	N	5962	6400	6235	6087	6168	
30 %	SPECIMEN NO.	5	15	26	14	-	15700
	N	16300	15548	15308	15717	-	
20 %	SPECIMEN NO.	6	16	17	34	-	34800
	N	34712	36421	33782	34510	-	

N = NUMBER OF CYCLES TO FAILURE

TABLE 31.

SUMMARY OF FATIGUE TESTS RESULTS
FREQUENCY 100 CPM

SERIES ES6 AGE 14 DAYS

R = MODULUS OF RUPTURE = 95 PSI

STRESS LEVEL							AVERAGE N
60 %	SPECIMEN NO.	7	8	18	27	-	21
	N	19	26	22	18	-	
50 %	SPECIMEN NO.	9	10	19	20	35	751
	N	790	740	800	730	695	
40 %	SPECIMEN NO.	11	21	22	28	-	16400
	N	16,020	16,900	16,790	15,900	-	
30 %	SPECIMEN NO.	12	23	24	29	30	34400
	N	34,950	34,860	34,300	33,900	34,200	
20 % {*22.5 %}	SPECIMEN NO.	36	XII.	37	38		4 75,000 ×1,73,650
	N	*1,72,970	*174380	4,67,800	4,82,200		

N = NUMBER OF CYCLES TO FAILURE

TABLE 32.

SUMMARY OF FATIGUE TESTS RESULTS

FREQUENCY 100 CPM

SERIES ES8 AGE 3 DAYS

R = MODULUS OF RUPTURE = 125 psi

STRESS LEVEL							AVERAGE N
60 %	SPECIMEN NO.	1	2	13	25	37	23
	N	26	19	24	21	25	
50 %	SPECIMEN NO.	3	4	14	26	27	510
	N	537	498	522	508	485	
40 %	SPECIMEN NO.	5	6	15	16	28	19900
	N	20660	19350	21070	18800	19620	
30 %	SPECIMEN NO.	17	18	30	40	–	34310
	N	33680	35790	34280	33500	–	
20 %	SPECIMEN NO.	(i)	(ii)				>1 MILL.
	N	>1 MILL.	>1 MILL.				

N = NUMBER OF CYCLES TO FAILURE

TABLE 33

SUMMARY OF FATIGUE TESTS RESULTS

FREQUENCY 100 CPM

SERIES ES8 AGE 14 DAYS

R = MODULUS OF RUPTURE = 150 psi

STRESS LEVEL							AVERAGE N
60 %	SPECIMEN NO.	7	19	31	32		49
	N	53	51	45	48	–	
50 %	SPECIMEN NO.	8	20	21	45	46	3350
	N	3184	3305	3266	3490	3502	
40 %	SPECIMEN NO.	9	10	22	47	48	30900
	N	30480	31560	30070	29940	32450	
30 %	SPECIMEN NO.	33	XIV	–	–	–	>1 MILL.
	N	>1 MILL.	>1 MILL.	–	–	–	
20 %	SPECIMEN NO.	–	–	–	–	–	
	N	–	–	–	–	–	

N = NUMBER OF CYCLES TO FAILURE

TABLE 34

SUMMARY OF FATIGUE TESTS RESULTS

FREQUENCY 100 CPM

SERIES ES 10 AGE 3 DAYS

R = MODULUS OF RUPTURE = 165 psi

STRESS LEVEL							AVERAGE N
60 %	SPECIMEN NO.	7	8	15	23	-	650
	N	703	670	592	640	-	
50 %	SPECIMEN NO.	9	16	17	24	-	5200
	N	5170	4980	5360	5290	-	
40 %	SPECIMEN NO.	10	18	25	26	-	33500
	N	34680	32570	33100	34150	-	
30 %	SPECIMEN NO.	27					>1 MILL
	N	>1 MILL	DID NOT	BREAK			

N = NUMBER OF CYCLES TO FAILURE

TABLE 35

SUMMARY OF FATIGUE TESTS RESULTS

FREQUENCY 100 CPM

SERIES ES 10 AGE 14 DAYS

MODULUS OF RUPTURE= 207 psi

STRESS LEVEL							AVERAGE N
60 %	SPECIMEN NO.	1	2	11	12	-	930
	N	980	890	930	920	-	
50 %	SPECIMEN NO.	3	4	5	13	-	8900
	N	8490	8660	9300	9150	-	
40 %	SPECIMEN NO.	6	14	19	-	-	64900
	N	64800	65780	64210	-	-	
30 %	SPECIMEN NO.	20	(I)	-	-	-	> 1 MILL
	N	> 1 MILL	> 1 MILL	DID	NOT	BREAK	

N = NUMBER OF CYCLES TO FAILURE

PLATE I

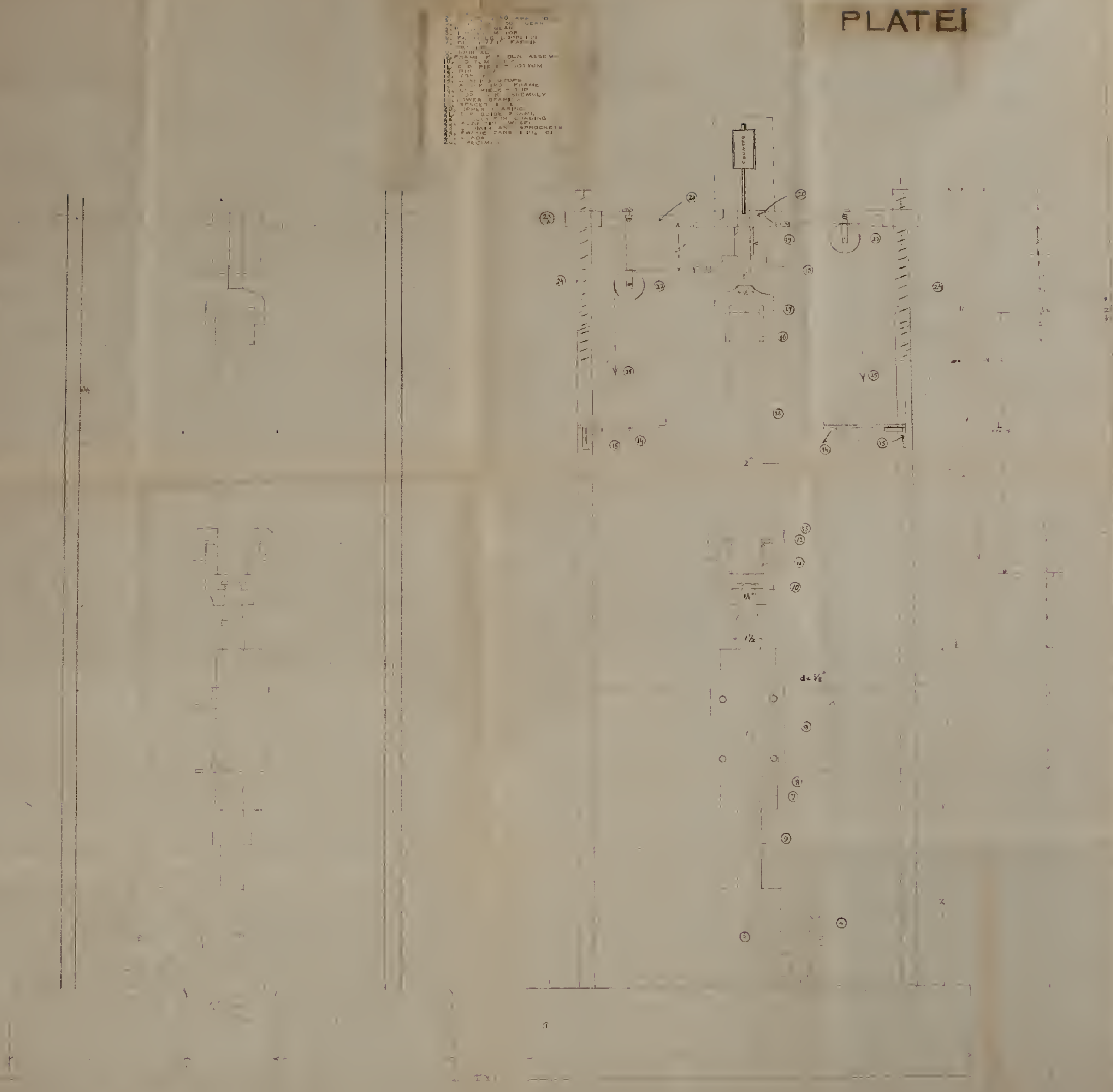


PLATE 2

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